TITLE THE GEOLOGY OF THE CORRIEYAIRACK PASS AREA, INVERNESS-SHIRE

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AUTHOR PAULA JILLIAN HASELOCK.

The Geology of the Corrieyairack Pass Area, Inverness-shire.

Paula Jillian Haselock

A thesis submitted for the degree of Doctor of Philosophy,

University of Keele.

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VOLUME ONE

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"He thought it almost a miracle to escape unhurt from such horrid wastes, roaring torrents, unwholesome vapour and frightful fogs; drenched from top to toe, frozen with cold, and half dead with fatigue."

Account of a journey across the
Corrieyairack Pass (1798)
from J.B. Salmond (1934)

ABSTRACT

Detailed mapping of 100 sq.km. around the Corrieyairack Pass, Inverness-shire, has revealed the presence of two distinct lithostratigraphic successions within dominantly psammitic metasediments. The two successions have been lithologically subdivided into nine formations. The upper Corrieyairack Succession is overlain conformably by Leven Schists of the Lochaber Subgroup of the Dalradian, and is in tectonic contact with the lower Glenshirra Succession. Both successions are geochemically and lithologically distinct from the Lower Dalradian and are considered to be part of the Grampian Division.

Three episodes of deformation are recorded. An early phase is represented by minor isoclinal folds, a penetrative schistosity and the development of the Gairbeinn Slide, which now separates the two successions. A model suggesting the presence of major recumbent D1 folds is proposed based on evidence obtained from the Tarff Gorge.

The second episode of deformation, represented by major NE-SW trending tight, upright folds and abundant congruent minor folds with an axial planar cleavage, is the dominant control on the regional outcrop pattern. The third episode consisting of major N-S trending open folds is recognised on a macroscopic scale as a result of the variation in attitude and trend of the D2 structures.

A geochemical study of the metasediments and associated calc-silicate bands was undertaken in an attempt to distinguish between the different formations and successions and as an aid to the interpretation of the metamorphic and sedimentary histories of the area. There is a systematic variation in petrology and geochemistry between the two successions which is a product of original sedimentary differences.

Two principal metamorphic peaks have been recognised, both of middle amphibolite facies, with kyanite locally developed in semi-pelites and bytownite and clinopyroxene in calc-silicate bands, during M_1 in the south-east of the area.

A brief survey of the igneous rocks was also undertaken.

ACKNOWLEDGMENTS

The research for this thesis was carried out during tenure of a Keele University Research Studentship which is gratefully acknowledged, together with additional financial assistance for field work from the Department of Geology.

I would also like to thank the staff and fellow research students in the Department of Geology, particularly; my supervisor, Dr J.A. Winchester, for introducing me to the Corrieyairack Pass area and his help and encouragement at Keele; Dr R.G. Park and Mr R. Strachan for their numerous and lengthy discussions; Mr G. Lees and Mr J. Lockett for help with geochemical and computing problems; and members of the technical staff, especially Mr D. Emley for help with various analytical techniques and Miss P. Douglass for photographic work.

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1. LOCATION AND EXTENT OF AREA

The Corrieyairack Pass area lies in the southern part of the Monadhliath Mountains, of Inverness-shire, approximately fifty kilometres south-west of Inverness, (Figure 1.1). It covers approximately one hundred square kilometres of moorland, on the watershed between the north-flowing River Tarff and the east-flowing River Spey.

The Corrieyairack Pass itself, 780m above sea level, is crossed by a military road, built in 1735 by General Wade.

Beyond Melgarve the road is now suitable only for land rover and together with estate tracks from Culachy Farm running parallel to the River Tarff, and a landrover track across Glen Doe Forest, provides the only access to the area.

The land is divided between five estates: Glen Doe, Culachy, Glenshirra, Brae Roy, and Aberchalder, and used for sheep and cattle grazing and deer stalking. There are no permanent dwellings in the area.

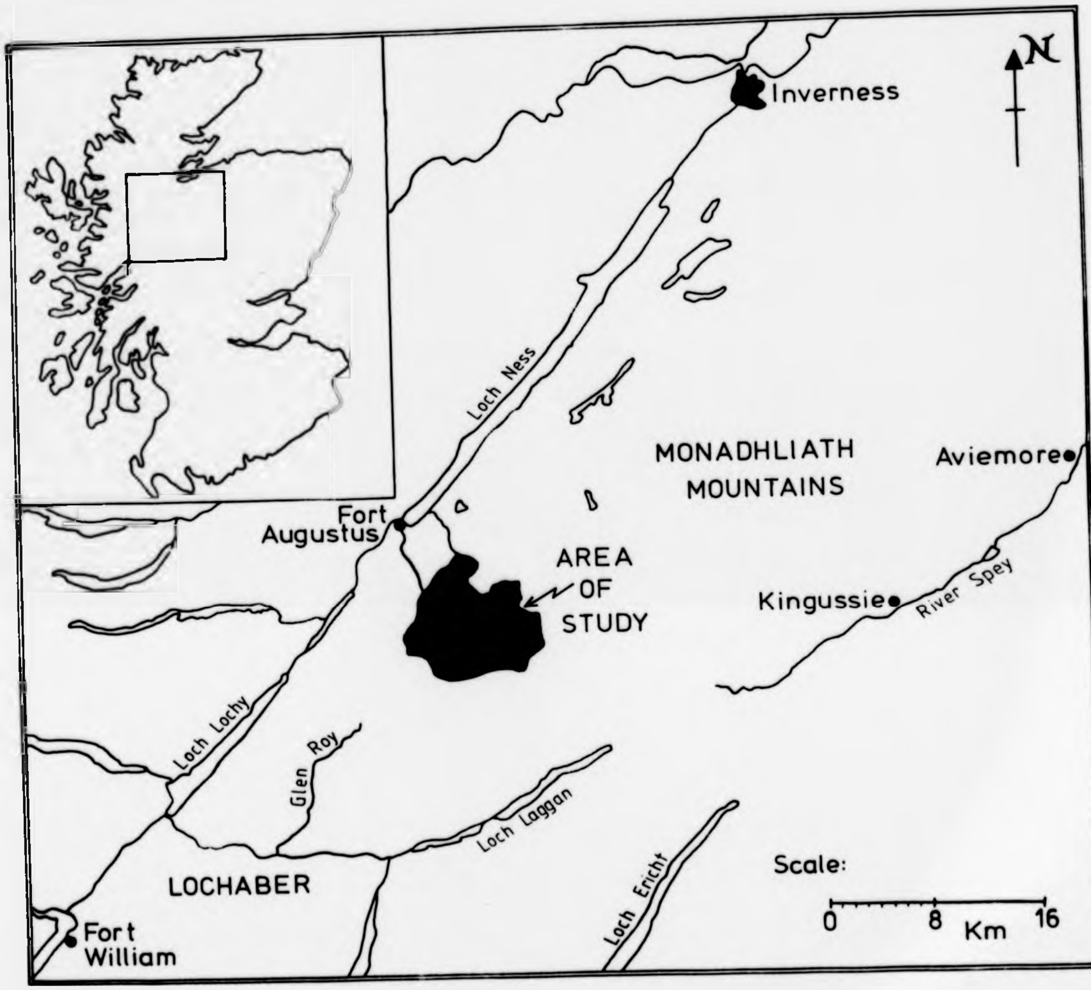


Figure 1.1: Location of area of study.

2. PHYSIOGRAPHY

The area consists of a plateau varying between 700 and 800 metres above sea level, deeply dissected by the Rivers Tarff and Spey and their tributaries.

The River Spey occupies a broad 'U' shaped glacial valley, with a flood plain up to 0.75 km wide containing the meandering river. Its tributaries are generally gently flowing streams in wide 'U' shaped valleys separated by rounded hills covered with extensive peat deposits.

In contrast, the River Tarff, for much of its length occupies a narrow gorge, up to 100m deep. As a result of the overdeepening of the Great Glen by glacial action, which caused the rivers flowing into the Glen to cut down into their glacial valleys, the tributaries of the River Tarff also drop steeply down the valley sides with numerous waterfalls and waterslides producing well washed exposures. However, particularly in the lower reaches of the Tarff, the steep sides of the gorge render access difficult.

Hillside exposure is invariably lichen covered and deeply weathered. The ice mass which produced the Great Glen, also produced numerous small basins on the surrounding uplands, especially on the Glen Doe Forest resulting in up to 50% exposure on Carn a' Chuilinn with numerous lochans. Further south deposits of peat are more extensive and exposure is limited to the steeper slopes and stream sections. Much of the northeastern part of the area, is very poorly exposed, consisting of a plateau at approximately 700m O.D. with a few scattered outcrops in an expanse of bog and thick peat deposits.

3. AIMS AND SCOPE OF RESEARCH

Detailed mapping, on the scale of six inches to the mile was undertaken in the Corrieyairack area during the Easter and Summer vacations of 1979 and 1980, as a continuation of work carried out by Whittles in the Killin area, to the north, with the object of establishing a stratigraphic sequence and elucidating the structure of a relatively unknown area, in the upper part of the Grampian Division of the Moine assemblage.

It was also hoped to be able to establish the stratigraphic and structural relationships between the Monadhliath and Leven Schists, and the location of the Moine - Dalradian boundary.

Extensive sampling of the various lithostratigraphic divisions established, was also undertaken with a view to producing geochemical 'fingerprints' for the various lithologies, and building up a metamorphic history of the area, with particular attention to the geochemistry and petrography of the calc-silicate pods and bands present in many of the formations. Geochemical analysis of the metasediments and igneous bodies was undertaken using X.R.F. techniques at the University of Keele.

The monotonous nature of the lithologies, and the discontinuous nature of many of the local variations made the lithostratigraphical subdivision of the psammitic lithologies necessarily rather vague, and the generally poor exposure and problems of access in much of the area added to the difficulties of sampling on a statistically valid basis.

4. PREVIOUS RESEARCH AND GENERAL GEOLOGICAL BACKGROUND

The first detailed geological study of the Southern Monadhliath Mountains was carried out by J.G.C. Anderson (1956) who mapped an area, extending from Loch Treig and Glen Roy in Lochaber, to the headwaters of the Rivers Spey and Findhorn, between the years 1936 and 1954.

As a result of this work he subdivided the stratigraphic succession into: the Moinian Eilde Flags overlain by a variable series of pelites and impersistent quartzites of the Monadhliath Schists or Transition Group, in turn succeeded by Dalradian limestones, the Kinlochlaggan and Ballachulish Limestones of the Basal Calcareous Group.

Within the Eilde Flags, he included the Central Highland Granulites of the Spey and Findhorn and the Struan Flags of Glen Garry, all dominantly psammitic metasediments. At the top of the Eilde Flags he described micaceous quartzites, gradational with the Eilde quartzite at the base of the transition group, followed by the Monadhliath Schists, (Table 1.1).

Anderson considered that the dark coarse garnetiferous mica schists of the Monadhliath Schist, especially well developed around Loch Killin and the Corrieyairack Pass, were equivalent not only to the fine grained, silvery grey, schists of Glen Roy, and the Leven Schists of Lochaber but all the mica-schists of the Lochaber Subgroup. The disappearance of the two quartzites which allow the subdivision of the Lochaber Schists was explained by a northwesterly lateral facies change.

Anderson also considered that the base of the Dalradian Supergroup should be drawn at the base of the lowest limestone, with the quartzite-pelite assemblage of Lochaber representing a transition group.

TABLE 1.1

from Anderson (1956)

GROUP	CHARACTERISTIC ROCK TYPE	CORRELATIONS: Lochleven to Glen Roy (Bailey 1934)	CORRELATIONS: Central Highland Succession Anderson (1948b)
Kinlochlaggan Limestone	Limestones, calc-schists and mica-schists	Ballachulish Limestone	Dalradian Basal Calcareous Group
Kinlochlaggan Quartzite	Quartzite	Leven Schists Glen Coe Quartzite Binnein Schists	
Monadhliath Schist	Mica-schists with granulite ribs and Carbonaceous layers and impersistent quartzites	Binnein Quartzite Eilde Schists	Pelitic and Quartzitic Transition Group
Eilde Quartzite (impersistent)	Quartzite	Eilde Quartzite	
Eilde Flags	Flaggy biotite-granulites with pelitic beds, locally highly siliceous especially towards the top	Eilde Flags	Central Highland Psammitic Group

M O I N I A N

Stratigraphic Succession of Moinian and Dalradian Strata, Glen Roy to Monadhliaths.

Three major NE-SW trending folds were recognised: the Kinlochlaggan Syncline, in the east, with the Kinlochlaggan Limestone at its core, the Loch Laggan Anticline and in the west the Corrieyairack Syncline, with the Monadhliath Schist at its core. Both synclines were described as nearly isoclinal with near vertical axial planes. The intervening Lochlaggan Anticline formed a broad upfold of Eilde Flags and at the west end of Loch Laggan was described as a tight upright structure, however further north the northwestern limb passed through vertical and became overturned. Anderson also mapped the Corrieyairack and Allt Crom Granites and numerous minor intrusions, including 'porphyrite' and microdiorite types of the Ben Nevis Swarm and also felsite and porphyry dykes.

More recently detailed mapping has been completed in the Loch Killin area by Whittles (1981) elucidating the structure and establishing a stratigraphic succession, around the core of the Corrieyairack Syncline, which has formed the basis for the stratigraphic work in the Corrieyairack Pass. Liverpool University and the Institute of Geological Sciences, have also been involved in a project to map areas adjacent to the Great Glen Fault, in which the work of Parson and Highton is particularly relevant to the regional correlation of the rocks of the Corrieyairack Pass, (Figure 1.2).

The similarity between rocks of the Central Highlands and those of the North West Highlands was first recognised by Murchison and Geikie (1861). They described the grey quartzose beds of Loch Eil, which they thought were folded about an anticlinal arch along the line of the Great Glen, and thus recurred around Glen Spean. Before 1892, all the rocks east of the Moine Thrust, were termed 'Dalradian', although Geikie (1892) recognised the presence of 'Moine Schists' in the Northern Highlands which were different in character from the Dalradian rocks southeast of

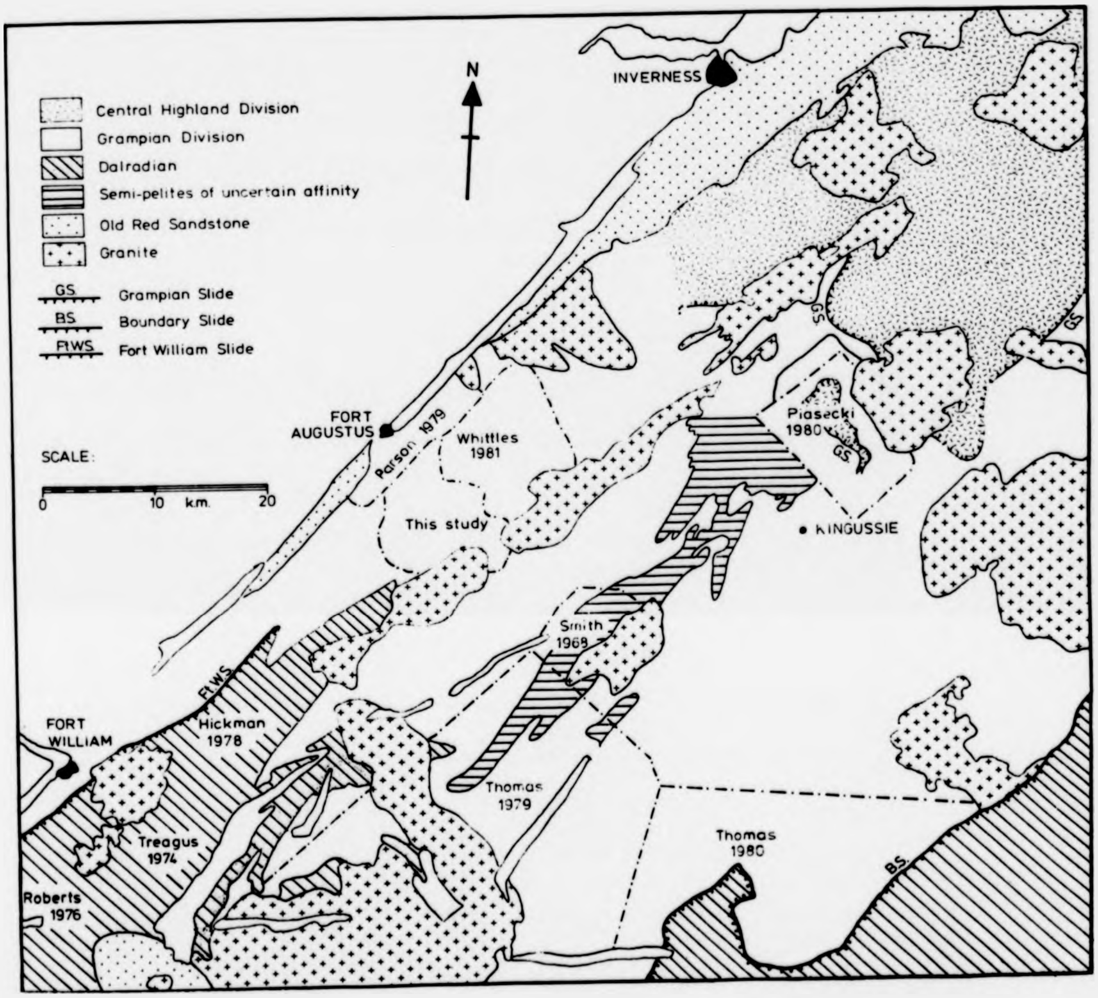


Figure 1.2: General geology and recent research areas in the Central Highlands.

the Great Glen.

Later work established that rocks of similar appearance to the 'Moine Schists' could also be identified south of the Great Glen Fault. Two main types of metasediment were distinguished: 'granulites' and 'mica-schist' (Hinxman et al, 1913), and the term Central Highland Granulites was introduced (Hinxman & Anderson, 1915) to describe 'undifferentiated siliceous and quartzofeldspathic schists' with belts of 'pelitic and semi-pelitic schists and gneisses'. They also described garnetiferous 'zoisite-granulites' occurring as bands within the 'granulitic' biotite schists and gneisses.

The Monadhliath Schist (Anderson, 1956) was first recognised by Peach and Horne (1930) who recorded a belt of 'pelitic gneiss' traceable 'from the basin of the Findhorn to the Monadhliath Mountains', affected by intense folding and overfolding, causing considerable variation in strike from the dominant NE-SW trend.

The Dalradian and Moine assemblages, as they were now recognised, were found to be notably different, with the Moine consisting mainly of psammitic and pelitic rocks, while Dalradian was lithologically diverse and apparantly originated in a different depositional environment, (Hickman, 1978). However, there has been much discussion over the location and nature of the boundary between the two successions.

The work of Bailey (1934) placed this boundary below the Eilde Quartzite, the lowest of the series of diversified rocks, stratigraphically overlying the Central Highland Granulites represented by the Eilde Flags (see Table 1.1) and this has since become the accepted practice (Johnstone, 1966). Anderson (1948, 1956, 1978), however, continues to place the boundary below the lowest limestone in the sequence, the Ballachulish limestone.

Johnstone et al.(1969, 1975) re-emphasised the correlation of the Central Highland Granulites of the Grampian Highlands with the Moinian of the Northern Highlands, suggesting that they represent the youngest rocks of the 'Moinian Assemblage'. They suggested that the 'younger Moines', showing only Post-Cambrian, Caledonian metamorphism, might rest unconformably on 'older moines' which have suffered in addition Pre-Cambrian metamorphism.

Harris, et al.(1978) however, proposed that the Central Highland Granulites had greater affinities to the 'Dalradian Supergroup'. They distinguished the Central Highland granulites from their most similar counterparts of the Northern Highlands, the Loch Eil Division, by suggesting that the Loch Eil Division had suffered a Pre-Cambrian orogenic event. They stated that this was indicated by the apparent structural conformity of the Division with the Ardgour Granitic Gneiss, dated at 1050M.a. (Brook et al., 1976), whereas the Central Highland Granulites and the Dalradian were affected only by Caledonian events.

Although elsewhere the Moine-Dalradian contact is recognised as a tectonic junction (Roberts,1976, Rast,1957, Roberts and Treagus,1975,1977), the granulites in the Lochaber area pass up through a normal sedimentary transition through the Lochaber Transition Group into the Ballachulish Group of the Dalradian (Hickman, 1978). The contention that this junction is also tectonic (Lambert, 1975) is not generally accepted by others who have made a detailed study of the Dalradian in the area (Treagus,1974, Hickman,1975). It is considered, therefore, that no great unconformity exists between the Central Highland Granulites and the Dalradian and it was proposed (Harris et al., op.cit.) that the Central Highland Granulites formed a part of the Dalradian Supergroup which they termed the Grampian

Group. It was noted that not all of the rocks formally assigned to the Central Highland Granulites may be part of the Grampian Group as autochthonous strata and that rocks which have suffered Pre-Cambrian orogenesis may occur south-east of the Great Glen Fault.

More recent work in the Spey Valley (Piasecki,1980, Piasecki & Van Breemen,1979a, 1979b) has shown that part of the Central Highland Granulites has undergone Pre-Cambrian orogenesis, and a 'basement-cover' relationship of 'younger and older' Moines was proposed. The basement, 'Central Highland Division' which has yielded Rb/Sr ages between 950 and 1300Ma, is separated from the 'cover' (Grampian Division) by a complex zone of repeated sliding, termed the Grampian Slide. Pegmatites intruded into and deformed by the slide zone have produced Rb/Sr dates from 718 ±19Ma to 573 ±13 Ma, comparable with 'Morarian' pegmatites (730 ±20Ma) (Van Breemen, Pidgeon and Johnson, 1974) in the Morar Division northwest of the Great Glen. These are considered by Piasecki (1980) to indicate a 'Morarian' age for the early sliding between the two divisions while subsequent Palaeozoic movement on the slide zone, reset the Morarian ages, so that ages younger than 573 ±13Ma have also been obtained. The Grampian Division metasediments in the slide zone must therefore be somewhat older than 718Ma.

Much of what Anderson originally mapped as the Monadhliath Schist on Speyside, now appears to form part of the 'older' Central Highland Division but the remaining 'Eilde Flags' are included within the Grampian Division. The Dalradian sediments are considered to have accumulated between the Late Pre-Cambrian (Upper Riphean) and the Cambro-Ordovician (c. 500Ma) (Harris et al., op.cit.) with the sedimentary transition between the Moine and Dalradian occurring at c. 700Ma (Dunning, 1972). This would require a thick sedimentary pile, representing the Grampian Division, in which the deeper rocks were being affected by amphibolite facies metamorphism, whilst the younger rocks were still being deposited (Piasecki, 1980). Alternatively, an as yet unrecognised stratigraphic break may be present within the Grampian Division.

In contrast to the southern Monadhliath Mountains, the Lochaber region has been the subject of prolonged and heated debate from Bailey's original interpretation (1910) to Roberts and Treagus (1977) and Hickman (1975,1978). The general stratigraphy and structure of the region (Table1.1) is now fairly well established. Good marker horizons and facing directions, provided by sedimentary structures, enables large scale early recumbent folds, associated with slides to be recognised in a nappe complex (Johnstone 1966, p.15 & p.21). These are affected by later recumbent and upright folds, all associated with Caledonian deformation.

Large scale recumbent structures and associated slides have also been recognised in the Ben Alder and Schie hallion areas, affecting rocks considered to form part of the Grampian Division (Thomas, 1979, 1980) but within the Southern Monadhliaths no major recumbent structures have yet been recognised.

CHAPTER 2 : STRATIGRAPHY

1. INTRODUCTION
   - a. Previous Work
   - b. Methods of Subdivision

2. STRATIGRAPHY
   - a. Glenshirra Succession
     - i. Creag Mhor Psammite
     - ii. Carn Dearg Psammite
     - iii. Allt Luaidhe Semi-psammite
     - iv. Gairbeinn Pebbly Semi-psammite
   - b. Corrieyairack Succession
     - i. Coire nan Laogh Semi-pelite
     - ii. Fechlin Psammite
     - iii. Knockchoilum Semi-psammite
     - iv. Monadhliath Semi-pelite
     - v. Carn Leac Semi-psammite
   - c. Tarff Gorge Section

1. INTRODUCTION

a. Previous Work

As outlined in Chapter 1, the stratigraphic position of the rocks of the Monadhliath Mountains is the subject of much recent debate. Following the work of Piasecki (1979, 1980) it is considered that the dominantly psammitic lithologies of the Corrieyairack Pass, previously described as Eilde Flags or Central Highland Granulites (Anderson, 1948, 1956) form the upper part of the Grampian Division, directly underlying the Lochaber Subgroup of the Dalradian represented by the Leven Schists of Glen Roy. Although many workers have accepted that the Eilde Flags may form part of the Moinian Assemblage (Johnstone et al,1969, Hickman,1975), a direct link between the Grampian Division and the 'younger' moines of the North West Highlands has yet to be proved.

Until recently, few attempts have been made to subdivide the rocks of the Grampian Division. Anderson (1956) included all the Central Highland Granulites or Central Highland Psammitic Group within the Eilde Flags, although he recognised both psammitic and semi-pelitic lithologies. The dominantly psammitic metasediments were described as fine grained, grey, quartzo-feldspathic granulites with abundant small flakes of biotite, individual beds ranging from 3 inches to 1 foot in thickness and locally containing pale calc-silicate bands and current bedding.

Thomas (1979, 1980) subdivided the Grampian Division of the Strathtummel and Ben Alder areas into 3 subgroups on a lithostratigraphical basis, describing 4000 metres of dominantly psammitic metasediments with abundant and varied sedimentary structures consistently younging into the Lochaber Subgroup of the Dalradian. The Ben Alder succession consists of psammites and quartzites, banded semi-pelite and pelite with psammitic units and rare quartzites. The Drumochter Succession of psammites and semi-pelites and the youngest Strathtummel Succession, less than 800 metres in thickness, of psammites and quartzites with minor semi-pelites and quartzites with minor semi-pelites. These successions must occupy a similar stratigraphic position to the rocks of the Corrieyairack area, both lying immediately below rocks of the Lochaber Subgroup, but as the Grampian Division / Dalradian contact is possibly diachronous, the rocks of the two areas are probably not lateral equivalents and no direct correlations are possible. It may also be significant that the two areas are on opposite sides of the Ossian steep belt (Thomas, 1979) the nature of which has still to be resolved.

Working in the Loch Killin area, north of the Corrieyairack Pass, Whittles (1981) recognised four lithostratigraphic formations, in conformable stratigraphic contact with each other and consistently younging towards the core of the Corrieyairack Syncline as demonstrated by widespread sedimentary structures.

The lowest formation recognised by Whittles (1981) on the north-western limb of the NE-SW trending Corrieyairack Syncline, in the River Fechlin, was termed by Whittles the Fechlin Psammite. It is overlain in turn by the formations termed by Whittles (op. cit.) respectively, the Knockchoilum Semi-psammite, the Glen Doe Semi-psammite and in the core of the syncline, the Monadhliath Semi-pelite. Working in the Corrieyairack Pass area it was possible to trace and extend this lithostratigraphic division and to recognise a further, separate succession, exposed in the SE of the region.

b. Methods of Lithostratigraphic Subdivision

Subdivision of the metasediments of the Corrieyairack area was possible after detailed outcrop mapping, on the basis of variations in overall lithological characteristics. Small scale and local facies variations were noted and contributed to the overall definition of each formation recognised. Lithological variation is considered to represent differences in the original sediment although deformation and metamorphic recrystallization has obliterated much of the original sedimentary fabric.

Sedimentary structures including cross bedding, cross lamination, planar, convoluted and graded bedding, together with the presence or absence of calcareous bands and pods of various types, (Chapter 6) also contributed to the definition of the formations taking into account the state of strain in a particular area.

The various lithologies were classified, in the field, into one of five groups:

Quartzite

Psammite

Semi-psammite

Semi-pelite

Pelite

together with interbanded combinations of these. Boundaries between these five groups are gradational and therefore dificult to define but depend principally on the proportions of mica to quartzo-feldspathic minerals present (Chapters 3 & 4).

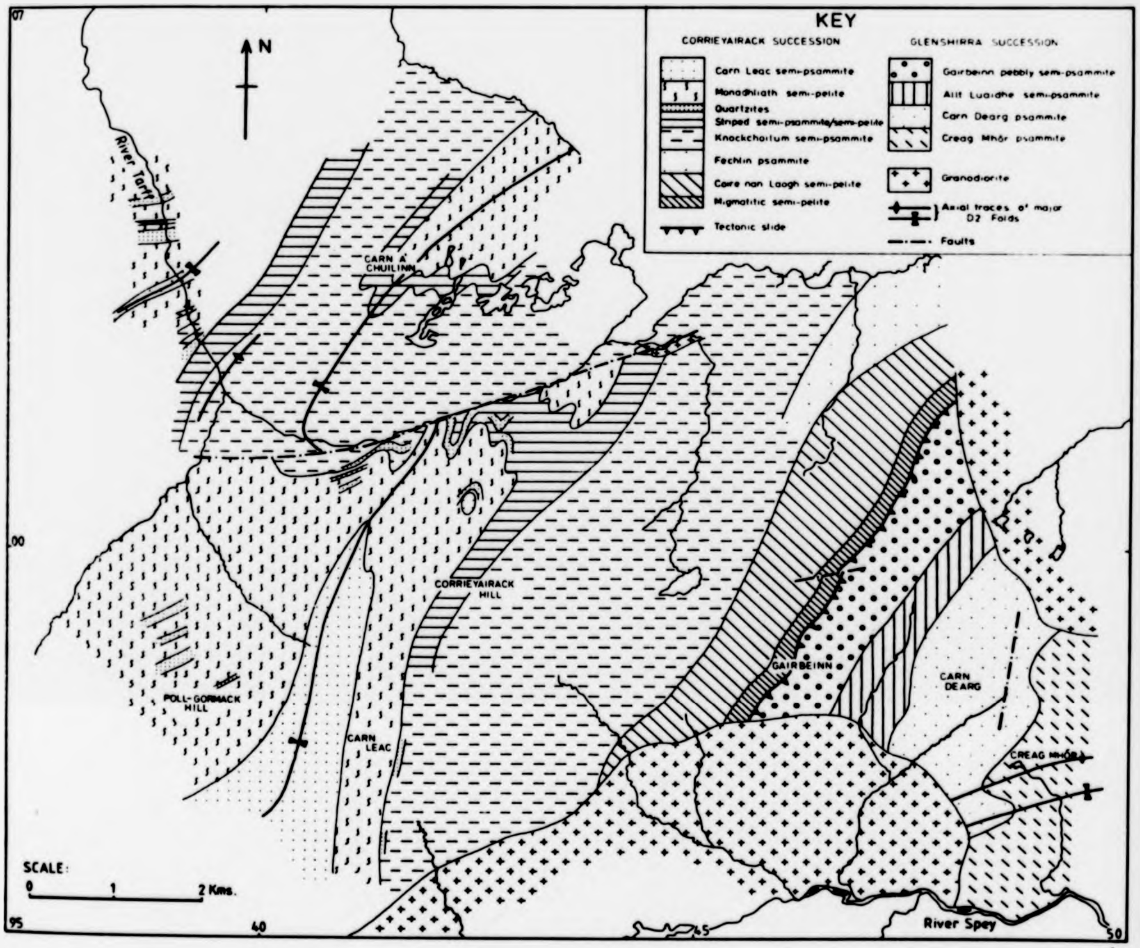


Figure 2.1: Distribution of litho-stratigraphic formations.

Table 2.1

		FORMATION	THICKNESS (metres)
Dalradian	Lochaber Subgroup	Leven Schists	--
Grampian Division	Corrieyairack Succession	Carn Leac Semi-psammite	> 500
		Monadhliath Semi-pelite	620
		Striped Psammite/Semi-pelite	250 } - 1800
		Knockchoilum Semi-psammite	
		Fechlin Psammite	0 - 640
		Coire nan Laogh Semi-pelite	150 } - 840
		Migmatitic Semi-pelite	
		GAIRBEINN SLIDE	
	Glenshirra Succession	Gairbeinn Pebbly Semi-psammite	670
		Allt Luaidhe Semi-psammite	590
		Carn Dearg Psammite	740
		Creag Mhōr Psammite	> 600
			TOTAL=7000

STRATIGRAPHIC SUCCESSION OF THE ROCKS OF THE CORRIEYAIRACK PASS

2. STRATIGRAPHY

Two distinct lithostratigraphic successions have been recognised in the Corrieyairack area, the lower Glenshirra Succession and the structurally higher Corrieyairack Succession, separated from each other by a tectonic discontinuity. As a result of this discontinuity the two successions cannot be related to each other and there are no immediately comparable lithologies. The two successions may therefore represent either contemporaneous strata juxtaposed by early sliding or strata of different ages (Chapter 7).

A summary of the stratigraphy and thicknesses of each formation is given in Table 2.1.

a. The Glenshirra Succession

The Glenshirra Succession outcrops in the southeastern part of the area mapped, between the Allt Crom and Corrieyairack Granodiorites, (Enclosure 1).

Using the criteria previously described the succession has been divided into four lithostratigraphic formations, for convenience given local names:

i. Creag Mhór Psammite

This is the lowest formation recognised in the Corrieyairack area, forming the southeastern side and summit of Creag Mhór (NN 486973) and all of Creag Beag (NN 482959). The base of the formation is not seen and the top contact is gradational with the overlying Carn Dearg Psammite.

Although designated a psammite, the Creag Mhór formation consists of at least 600 metres of a varied assemblage of psammites, semi-psammites, semi-pelites and a striped semi-pelite/semi-psammite lithology. Psammites make up over 50% of the formation and vary from massive, pink-weathering units up to 1m thick, with little or no indication of bedding or foliation, forming large joint blocks, to 15cm thick flags with thin micaceous laminae defining planar bedding.

Semi-psammites are finely striped, weathering into units ranging from 4 to 15cm thick with uniform planar bedding marked by thin micaceous laminae. They also occur in rapid alternations with semi-pelite bands up to 10cm thick, each band traceable for more than 5m laterally.

The formation becomes increasingly pelitic towards the top, which is marked by a more persistent semi-pelite band. Within the lower psammitic lithologies semi-pelite bands occur sporadically: these are lensoid in shape, averaging 1m, but reaching 5m in thickness.

Towards the top of the formation, there is possibly a cyclic repetition of psammitic and pelitic lithologies, with pink weathering psammites in 15cm flags and thin micaceous laminae, approximately 2m thick followed by 2m of semi-pelite, 2m psammite/semi-psammite in 30cm flags, and a further 2m of the pink weathering psammite, (Figure 2.2).

Calc-silicate bands and pods are extremely rare, within the formation, but white calc-silicate pods, up to 25cm long and 10cm thick do occur within the psammites and semi-psammites near the visible base of the formation.

ii. Carn Dearg Psammite

The Carn Dearg Psammite occurs on the northwestern side of Creag Mhór, in the poorly exposed ground of the Allt Féith a' Mhoraire valley and over the well exposed summit of Carn Dearg (NN 481985) attaining a maximum thickness of 740 metres.

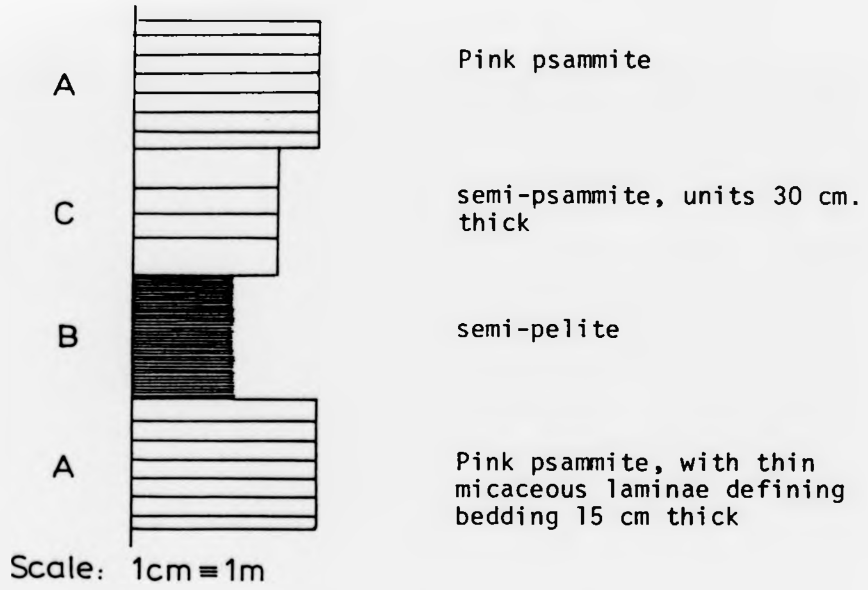


Figure 2.2: Rhythmic units in the Creag Mhór Psammite.

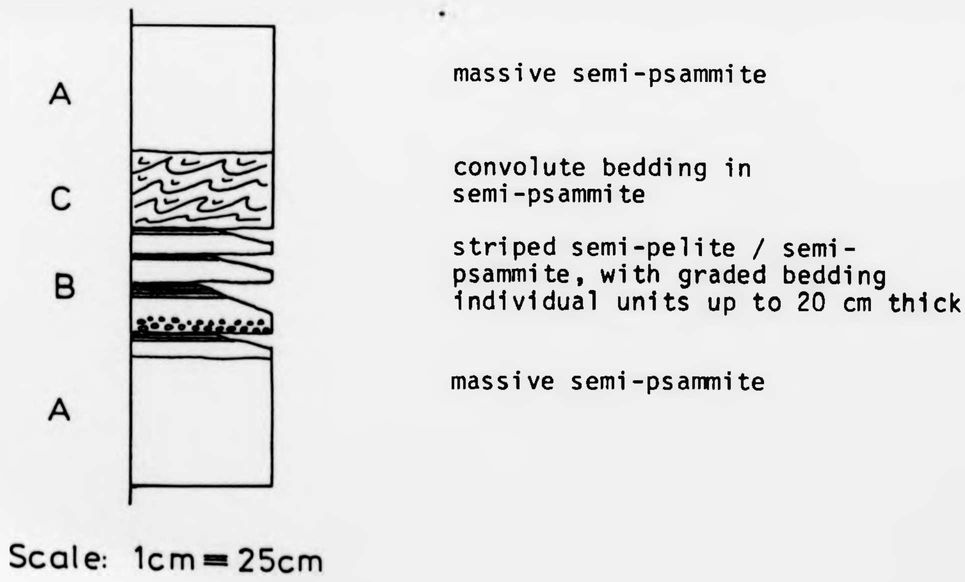


Figure 2.3: Rhythmic units in the Knockchoilum Semi-psammite.

In contrast to the underlying Creag Mhór Psammite the formation is 90% psammite with impersistent semi-psammites developed at the base, grading down into the semi-pelitic band marking the top of the Creag Mhór Psammite. The semi-psammites are well banded in flaggy units approximately 15cm thick separated by thin semi-pelite laminae.

The psammites are massive and buff-weathering with indistinct bedding occasionally marked by rich laminae up to 1cm thick, individual units can exceed 1m in thickness, but are generally between 30 and 50cm thick. They are well jointed and weather into large blocks. Where bedding is marked by mica laminae small scale cross-lamination can be recognised, which invariably shows that the bedding is uninverted. Semi-pelite bands upto 10cm thick also occur between massive psammites. In the central portion of the psammite on Carn Dearg there is a larger lens of semi-pelite approximately 15m long and 5m thick (Chapter 4). The top of the formation is marked by the gradational appearance of dominantly semi-psammitic lithologies characteristic of the overlying Allt Luaidhe Semi-psammite.

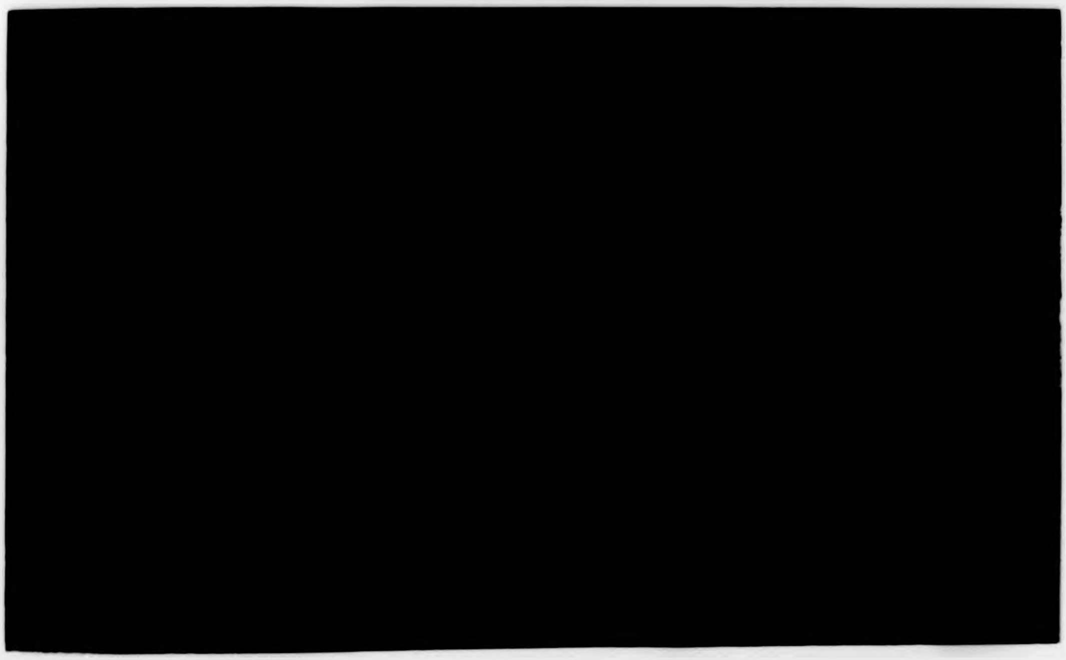
iii. Allt Luaidhe Semi-psammite

Exposed in the bed of the Allt Luaidhe and on the western side of Carn Dearg, the Allt Luaidhe Formation consists of thinly-bedded semi-psammites and psammites with subordinate semi-pelite and striped semi-psammite/semi-pelite bands. The formation varies in thickness from north to south from 490m to 590m.

The semi-psammites and psammites are often pinkish and are rich in haematite and pyrite. Individual units are 15-20cm thick. Some psammites contain coarse-grained bands with grains up to 2mm in diameter, thought to represent the original clasts. However, adjacent to the Corrieyairack Granodiorite, the semi-psammite lithologies have developed a coarse texture as a result of hornfelsing (Chapter 6).

Plate 2.1 : Striped semi-psammite/ semi-pelite in the Allt Luaidhe Semi-psammite (NN 46909782).

Plate 2.2 : 'Migmatitic' semi-pelite from the base of the Coire nan Laogh Semi-pelite (NH 47480162).



Semi-psammites and semi-pelites occur in rapid alternation, in units 4 - 6cm thick (Plate 2.1). The semi-psammite bands of this striped lithology occasionally contain cross-lamination indicating that the formation is uninverted. Like much of the formation especially in the south adjacent to the Corrieyairack Granodiorite these striped units contain numerous quartz veins, often strongly boudined and also pegmatite and granitic veins. Semi-pelites also occur in bands up to 2m thick containing thin semi-psammitic ribs. Thin poorly-developed white calc-silicate pods and bands 1 - 1.5cm thick and extending 15 - 20cm laterally occur in a few localities within the semi-psammite units.

iv. Gairbeinn Pebbly Semi-psammite

The first recognisable pebble band, within a dominantly semi-psammitic lithology, marks the base of the Gairbeinn Pebbly Semi-psammite, which forms the south eastern slopes of the NE-SW trending Gairbeinn ridge.

The formation with a thickness of 670 metres, consists of a poorly sorted, coarse grained semi-psammite with pebble bands up to 20cm thick, and subordinate semi-pelite and psammite bands.

The pebbles vary from 2mm to 6cm (y-axis) in diameter with a general increase in size towards the top of the formation and towards the north-east. The increase in grain size is accompanied by a change in composition from predominantly pebbles consisting of quartz and feldspar aggregates near the base, to pebbles of quartz aggregates near the top of the formation.

The pebbles occur in lenticular bands, averaging 10cm thick, which extend laterally for 2 or 3m. They become thicker and more frequent towards the top of the formation where they form small ridges in the topography. The pebbles are set in a dominantly semi-pelitic matrix.

(Plate 5.9).

Towards the base of the formation the pebble bands occur in small fining upwards cycles, up to 6cm thick, with a decrease in frequency of the pebbles representing a decrease in grain size and an increase of the proportion of mica across each unit (Plate 5.9). Between the pebble bands there are substantial thicknesses of psammites, semi-psammites and semi-pelites often in graded units 2 - 4cm thick. The semi-psammites and psammites also occur in more massive units up to 20cm thick which sometimes contain cross-bedding occasionally also evident in the pebble bands. However, all lithologies contain scattered clastic fragments. Thin white calc-silicate bands, 1cm thick, also occur sporadically within the semi-psammites.

The upper 300 metres of the unit displays a platy fabric while extreme rodding and flattening of the pebbles becomes evident in the top 150 metres. This is associated with the 'Gairbeinn Slide' (discussed in Chapter 7) which has obliterated original sedimentary features. It is not known however whether the slide has cut out any formations which may formerly have overlain the Gairbeinn Pebbly Semi-psammite.

b. The Corrieyairack Succession

The Corrieyairack Succession outcrops in the Corrieyairack Pass area and reaches a maximum thickness of 4400 metres. The constituent formations are repeated about the Corrieyairack Syncline (Enclosure 1).

The succession has been divided into five lithostratigraphic formations, three of which are those recognised in the Loch Killin area by Whittles (1981) (see Table 2.1).

i. Coire nan Laogh Semi-pelite

The lowest formation recognised in the Corrieyairack Succession is the Coire nan Laogh Semi-pelite, seen only on the south eastern limb of the Corrieyairack Syncline. It lies stratigraphically below the Fechlin Psammite which is the lowest formation recognised in the Loch Killin area (Whittles, 1981).

The semi-pelite outcrops on the northward facing slopes and summit of the Gairbeinn ridge (NN 461985), in the upper reaches of the River Tarff (NN 460995), in the Allt Yairack (NN 443071) and in Allt a' Mhill Ghairbh (NN 449800).

The formation, with a thickness of 840m, consists of semi-pelite with subordinate semi-psammites and quartzites, with a gradual increase in the proportion of semi-psammite towards the top of the formation.

The semi-pelites are generally dark grey-brown and fine grained, occurring in units 6 - 8cm thick, with ribs of semi-psammite and quartzite up to 10cm thick. In the River Tarff, directly underlying the Fechlin Psammite, the semi-pelites are finely jointed with a mauve-green colour due to the development of chlorite along planes of local shearing possibly a product of the competency contrast between the psammite and semi-pelite lithologies or local faulting. Further southwest, the Coire nan Laogh Formation becomes more psammitic occurring in bedded units up to 10cm thick and grading up into the overlying Knockchoilum Semi-psammite. Semi-psammites and thin quartzite ribs also occur locally towards the base of the formation.

White calc-silicate bands are abundant in the semi-pelites and are especially well developed on the northwestern slopes of Gairbeinn , (NN 459989). They range up to 10cm in thickness and are traceable

Plate 2.3 : Striped psammite/semi-pelite at the top of the Knockchoilum Semi-psammite (NH 403037).

Plate 2.4 : Monadhliath Semi-pelite from Meallan Odhar (NH 391004) showing strong S_1/S_2 foliation.

laterally for 1 - 2m. No sedimentary structures have been observed in the formation.

The basal 150 metres of the semi-pelite have a coarse-grained migmatitic texture and contain small quartzo-feldspathic segregations obscuring original sedimentary features (Plate 2.2). No calc-silicate bands were found. The grain size attains a maximum of 5mm in the centre of this basal zone and there is a sharp contrast at the base between relatively fine-grained semi-pelite containing quartzo-feldspathic segregations and the underlying Gairbeinn Pebbly Semi-psammite frequently obscured by felsite dykes. It is proposed that this texture and the sharp contact between the Corrieyairack and Glenshirra Successions are the effects of a tectonic discontinuity, 'the Gairbeinn Slide', discussed in more detail in Chapters 6 and 7.

The upper contact of this migmatitic semi-pelite with the remainder of the Coire nan Laogh Semi-pelite is gradational, with a decrease in grain size and proportion of quartzo-feldspathic segregations. Original lithological variation can be observed approximately 150m above the base where the semi-pelites show the coarsened texture but semi-psammitic ribs remain unaffected. Above occurs the normal fine grained semi-pelite.

ii. Fechlin Psammite

The Fechlin Psammite outcrops in the north east corner of the Corrieyairack area, where it attains a maximum thickness of 640 metres. The formation thins rapidly to the southwest possibly due to a facies variation and disappears within 2250 metres.

The psammites are well exposed in the upper reaches of the River Tarff where they are pale grey and fine grained. Individual units vary from 1m to 20cm thick and display convolute bedding (Plate 5.10), cross-lamination, planar bedding. Thin semi-pelitic laminae separate individual units and some stripy semi-psammitic units also occur. Calcite bearing pods and lenses approximately 8cm thick and 15cm long occur within the massive psammites.

Load casts and the cyclic repetition of graded units, and other sedimentary structures recorded in the River Fechlin, on the northwestern limb of the Corrieyairack syncline (Whittles, 1981) were not observed in this area.

iii. Knockchoilum Semi-psammite

The Knockchoilum Semi-psammite comprises nearly half of the Corrieyairack Succession. It covers a large part of the Glen Doe Estate, and outcrops on Carn a' Chuilinn, in the River Tarff, Allt Lagan a' Bhainne, Allt Uisg a' Chaime, on Corrieyairack Hill and in Allt Yairack (Enclosure 1).

The formation consists of 1800 metres of monotonous semi-psammites typical of Moine lithologies, with the local development of psammites and quartzites and a stripy lithology near the top of the formation.

In the Loch Killin area, Whittles (1981) subdivided the formation into an upper Glen Doe Semi-psammite, distinguished by the presence of white calc-cilicate bands and a lower Knockchoilum Semi-psammite characterised by the presence of green calc-silicates. White calc-silicate bands were not found within the semi-psammites of the Corrieyairack area, possibly due to facies variation and the subdivision of the formation was therefore not possible, the name Knockchoilum being applied to all the semi-psammites between the Fechlin Psammite and Monadhliath Semi-pelite.

The semi-psammites are pale grey and fine grained, occurring in flaggy units varying from 6cm to 1m in thickness, separated by semi-pelite bands up to 6cm thick. Coarse grained bands up to 6cm thick occasionally occur within the semi-psammites with grains up to 2mm in diameter and grading into semi-pelite before a local erosion surface. Thinner graded units occur which lack the coarse grained component.

Ripple cross-lamination up to 6cm in amplitude, are common, and convolute bedding is also locally preserved. These sedimentary structures are occasionally repeated in a cyclic pattern; with 50cm massive semi-psammite, overlain by 50cm of striped and graded semi-psammite/semi-pelite bands, individual bands 2 - 4cm thick with sharp erosional bases, in turn overlain by 30cm of convolute bedding (Figure 2.3), (Plate 5.8 & 5.12). Elsewhere the semi-psammites are massive and parallel bedded. The semi-psammites contain rare green calc-silicate bands up to 4cm thick, but calcite bearing pods and lenses reaching 1m in length and 10cm thick are more abundant (Plate 5.14).

Near the top of the formation in the Garbh Coire (NH 435018) and Bac nam Fuaran (NH 435009) the formation develops much more varied lithologies, in particular including striped semi-psammite/semi-pelite bands up to 20cm thick in rapid alternation over a thickness of 250m (Plate 2.3) and quartzite/psammite bands up to 20cm thick separated by thin semi-pelite bands. The quartzites occur as an impersistent and variable suite which often occurs at or near the base of the Monadhliath Semi-pelite but elsewhere never exceeds 10m in thickness. The striped lithology is traceable for 3km southwestwards, and on the northwestern limb of the syncline occurs on Carn Doire Chaorach (NH 490480) and in the Allt Sea n ghail, (NH 394024). Elsewhere the transition from the Knockchoilum Semi-psammites to the Monadhliath Semi-pelite is rapid, taking place over approximately 10m and in places it is marked by a platy fabric within the semi-pelites thought to be a result of the competency contrast between the two formations.

iv. The Monadhliath Semi-pelite

The Monadhliath Semi-pelite outcrops in three main areas, and does not form the continuous outcrop proposed by Anderson (1956).

The formation occupies the core of the Corrieyairack Syncline on Carn a Chuilinn (NH 471036) in a belt continuous with the outcrop in the Loch Killin Area. It is absent south of Carn a' Chuilinn due to the gentle NE plunge of the syncline, and only reappears south of the River Tarff due to the change in plunge of the syncline to a southwards plunge and the effects of the Sronlairig Fault (Chapter 5). The southern outcrop bifucates in Allt Coire na Céire (NH 421003) (Map 1) around the overlying Carn Leac Semi-psammite attaining a thickness of 620m and can be traced as far as the Corrieyairack Granodiorite in the south and on the northwestern limb of the syncline as far as Glen Roy (Haselock & Winchester, 1981). The formation also occurs within the Tarff Gorge (see Section C).

The formation consists almost entirely of semi-pelite with minor proportions of quartzite and semi-psammite and locally abundant white coloured calc-silicate bands. The semi-pelites are generally fine grained and dark grey, although locally silvery grey, and on Meallan Odhar (NH 399003), the semi-pelite is slightly coarser grained and segregated into quartz and feldspar and mica lenses (Plate 2.4). Quartz segregations or secretion lenses up to 10cm long and 4cm thick occur throughout the semi-pelite, but are more common on Meallan Odhar and in Allt Coire na Céire (NH 409010) (Plate 2.4).

Quartzite bands, varying from white to pink in colour, occur sporadically throughout the formation and although reaching 15m thick, individual bands cannot be traced for more than 500metres and are generally only 2 metres thick, with individual units varying from 6 to 15cm thick and containing no sedimentary structures. They bear little resemblance to the massive current bedded Eilde Quartzite of the Lochaber Subgroup, with which they have previously been equated (Anderson,1956, Piasecki,1975). The quartzites are more common towards the base of the formation where they also occur in a thinly striped lithology with semi-pelites, each band only 0.5 - 1cm thick.

The semi-pelites also contain ribs of semi-psammite with which the white calc-silicate bands are often associated. No sedimentary structures have been recognised.

The calc-silicate bands occur within the central portion of the formation and the semi-pelite near the base is devoid of calc-silicate bands. Nowhere are they as well developed as in the Monadhliath Semi-pelite of Loch Killin (Whittles, 1981) as they only reach 6cm in thickness, and are usually only 3 or 4cm in thickness, traceable laterally for 1 - 2m.

v. The Carn Leac Semi-psammite

The Carn Leac Semi-psammite is the highest formation recognised in the Corrieyairack area. It occurs south of Allt Coire na Céire (NH 412003) in the core of the Corrieyairack Syncline. It has been traced as far as the River Roy where it attains a maximum thickness of approximately 500m (Haselock & Winchester, 1981).

The formation has a gradational contact with the underlying Monadhliath Semi-pelite, and in the Allt Dubh (NN 386949) is overlain by silvery grey semi-pelites similar to the Leven Schist formation of the Lochaber Subgroup of the Dalradian. As the Carn Leac Semi-psammite has no proven lithological equivalent within the Lochaber Subgroup it is considered to be the highest formation of the Grampian Division in the Corrieyairack Area (Haselock & Winchester, 1981).

The semi-psammites are pale grey, and fine grained in units 4 - 20cm thick, separated by semi-pelitic bands up to 10cm thick. The formation becomes more psammitic southwards and towards the top with an increase in the average thickness of individual units.

The semi-psammites occasionally contain preserved cross-lamination and small scale graded units; they also contain calcareous bands 3 - 4cm thick and up to 1m long.

c. The Tarff Gorge Section

The rocks of the lower Tarff Gorge form a structurally complex area, in which the state of strain makes correlation with the formations of the rest of the Corrieyairack Succession difficult. The lithologies are extremely varied, ranging from psammites and quartzites to semi-pelites and pelites over the 3km length of the gorge. The structural interpretation of the section outlined in Chapter 7, suggests that the section consists of infolds of the Monadhliath Semi-pelite together with a small outlier of Carn Leac Semi-psammite repeated by D1 and D2 folding.

Semi-pelites comprise 80% of the section and are generally fine grained and silvery grey in colour with garnet porphyroblasts and abundant quartz segregation lenses and boudins. Locally the semi-pelites consist of small quartz and feldspar and mica lenses similar to the semi-pelites of the Meallan Odhar. No calc-silicate bands have been recognised. The striped lithology of Allt Sean gail (NH 394024) is followed by a quartzite band 10m thick followed by a striped psammite/semi-pelite lithology in which individual bands are 0.5 - 1cm thick. This is followed by a psammite with an early mylonitic fabric and an outcrop width of 800m of semi-pelite with occasional bands of semi-psammite. Flaggy grey semi-psammites with individual units up to 20cm thick occur at NH 390034, and these are thought to represent the Carn Leac Semi-psammite. Semi-pelites reoccur to the north with occasional thin quartzite bands, a thinly striped psammite/ semi-pelite lithology and quartzite bands up to 15m thick. The quartzite bands consist of white units between 4 and 30cm thick with thin semi-pelitic partings and also containing calcareous bands. They have a platy fabric marked by elongation of quartz and feldspar grains, no sedimentary structures were recognised. The Tarff Gorge Section is described in greater detail with reference to the complex structure of the area in Chapter 7.

CHAPTER 3 : PETROLOGY OF THE METASEDIMENTS

1. INTRODUCTION

2. SEMI-PELITES AND PELITES

   a. Migmatitic Semi-pelites

3. QUARTZITES

4. PSAMMITES AND SEMI-PSAMMITES

   a. Gairbeinn Pebbly Semi-psammite

1. INTRODUCTION

The metasediments of the Corrieyairack area have been divided in the field into five rock types: quartzites, psammites, semi-psammites, pelites and semi-pelites according to the relative proportions of mica, quartz and feldspar they contain. Subsequent modal analysis based on 1000 points for 32 representative samples of the different rock types resulted in the following definitions, although due to the subjective nature of the division in the field there is some overlap of the groups.

Table 3.1

ROCK TYPE	Quartz	Feldspar	Mica (%)
Quartzite	>70	<20	<10
Psammite	>50	>20	<20
Semi-psammite	80-60		20-40
Semi-pelite	60-30		40-70
Pelite	<30		>70

2. SEMI-PELITES AND PELITES

Semi-pelitic lithologies occur within all the formations in both the Corrieyairack and Glenshirra Successions, but they occur principally within the Monadhliath Semi-pelite formation, the Coire nan Laogh Semi-pelite and at the top of the Creag Mhór Psammite. Elsewhere the Semi-pelite and pelite bands are thin, lenticular and impersistent.

Biotite, quartz and plagioclase are essential constituents of the semi-pelites together with variable proportions of muscovite, apatite, sphene, zircon and opaques. Garnet, kyanite, fibrolite, andalusite, epidote, alkali feldspar and graphite are also found in some samples; their occurrence controlled both by the whole rock chemistry and variations in metamorphic conditions (see Chapter 4).

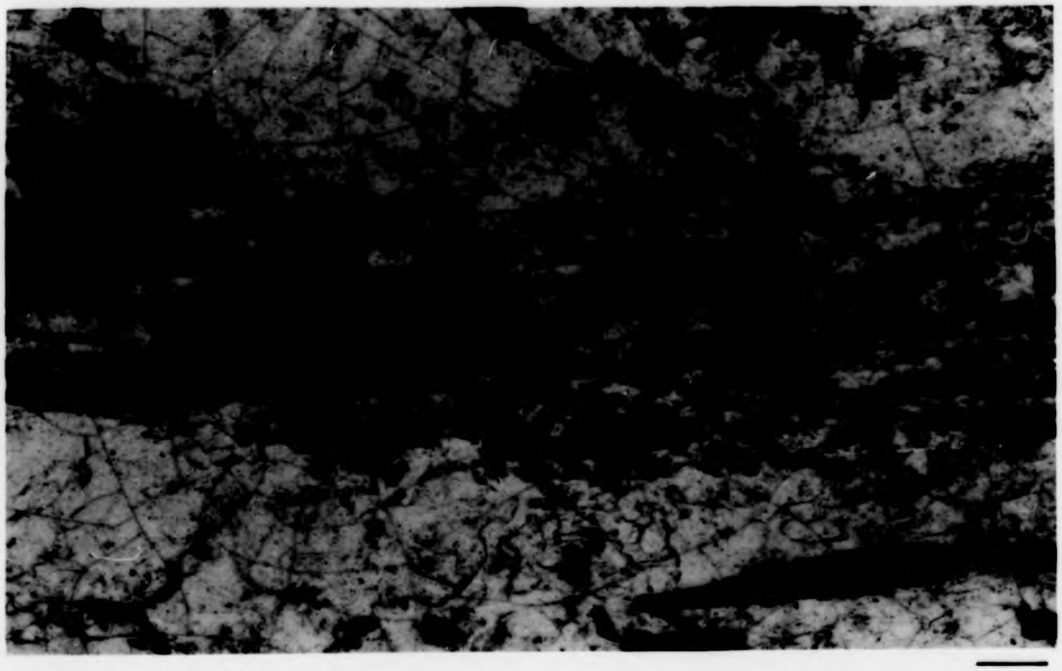
Semi-pelites from the Corrieyairack Succession can be distinguished from those of the Glenshirra Succession by the presence of garnet and red-brown biotite which contrasts with the dark-green/olive-green biotite from the Glenshirra Succession. These differences are discussed in more detail with reference to the geochemistry of metasediments (Chapter 4).

Biotite. Biotite from the Semi-pelites and Pelites of the Glenshirra Succession is pleochroic from olive-green to almost black (Z = black - dark green/brown, Y = olive green, X = yellow green) and occurs as elongate laths up to 2mm long with irregular embayed outlines but few inclusions. These laths are often surrounded by numerous minute grains of biotite in optical continuity with each other and the larger laths giving a shredded appearance (Plate 3.1). This texture also occurs, but more locally, within semi-pelites from the Corrieyairack Succession, particularly in the rocks which also contain kyanite, and is thought to be the result of a second episode of biotite growth. Altern-

Plate 3.1 : 'Shredded biotite' from semi-pelite from the Gairbeinn Pebbly Semi-psammite (plane polarised light).

Plate 3.2 : Crenulation of S_1/S_2 (top - bottom) by S_2 (left - right) (plane polarised light).

Scale bar represents 0.1mm




S2
S1

atively the fabric may be the result of shearing and mechanical disruption of pre-existing laths (See Spry,1969 p.235). However the widespread but irregular distribution of the fine grained biotite suggests that this origin is unlikely, and the assocation of this texture with the kyanite-bearing semi-pelites suggests it is possibly the result of reactions involving the production of kyanite.

The biotite from semi-pelites from the Corrieyairack Succession varies from brown to reddish-brown and contains numerous inclusions of zircon. The biotite laths are generally more idioblastic than those of the Glenshirra Succession with few embayed edges but they often show alteration along the cleavage to chlorite.

Muscovite occurs in variable proportions, from more than 50% of the total mica to a few flakes which are the result of late stage alteration. Where muscovite occurs as an early phase it occurs as thin laths elongate parallel to the dominant foliation. The laths have fairly high relief and a pale brown colour. The optic axial angle of the muscovite averages 15^{o}, indicating the presence of a high paragonite component, with substitution of Na for K in the muscovite structure. This occurs increasingly with increasing metamorphic grade (Lambert, 1959). Although more common within the Corrieyairack Succession, some semi-pelites of the Glenshirra Succession also contain up to 40% modal muscovite (Table 3.2). In both cases muscovite growth appears to slightly postdate biotite growth as the muscovite laths cross-cut the biotite.

Large muscovite porphyroblasts, consisting of randomly orientated and almost equidimensional laths, with few large quartz inclusions, cross cut the dominant foliation and overgrow the main fabric. These are obviously post-tectonic and may be associated with K metasomatism or contact metamorphism; intrusion of the granodiorite bodies resulting in the redistribution of muscovite already present in the rock. However, the porphyroblasts are not restricted to the proximity of the granodiorites and occur throughout the area.

TABLE 3.2: MODAL ANALYSES OF SEMI-PELITES AND PELITES

Sample no.	155	7869	7867	263	171	180	206B	191	72	268
Quartz	27	22	7	18	38	24	10	26	25	22
Plagioclase	23	13	8	9	16	23	22	22	15	16
K-Feldspar	tr	14	.5	-	-	-	-	-	-	12
Biotite	29	50	59	33	21	20	19	19	34	42
Muscovite	19	1	10	40	17	24	47	32	25	7
Garnet	-	-	-	-	4	5	.8	1	-	-
Kyanite	-	.3	7	-	-	-	-	-	-	-
Fibrolite	-	-	8	-	-	-	-	-	-	-
Calcite	-	-	-	-	-	.4	.3	-	-	-
Epidote	.5	.3	-	tr	-	-	-	-	-	tr
Sphene	-	-	-	-	-	.2	tr	-	-	-
Opaque	1	.3	.3	tr	4	1	tr	.3	.4	tr
Chlorite	-	-	-	-	-	2	.3	tr	-	tr
Tourmaline	-	-	-	-	.2	.2	.2	-	-	-
Apatite	.6	.3	.2	.5	.5	.3	.2	tr	.5	.2
Zircon	-	-	tr	-	tr	tr	tr	tr	tr	tr
Total	100.1	100.9	100.0	100.6	100.7	100.3	100.0	100.4	99.9	99.2

155: Creag Mhor Psammite
7869: Creag Mhor Psammite
7867: Creag Mhor Psammite
263: Carn Dearg Psammite
72: Creag Mhor Psammite
268: Creag Mhor Psammite

} Glenshirra Succession

171: Monadhliath Semi-pelite
180: Monadhliath Semi-pelite
191: Monadhliath Semi-pelite
206B: Knockchoilum Semi-psammite

} Corrieyairack Succession

Both biotite and the early muscovite laths show strong preferred orientations within the semi-pelites, defining a S_o/S_1 foliation. The S_1 foliation is a crenulation cleavage in many of the semi-pelites, with small biotite laths orientated at high angles to the dominant foliation within the quartz and feldspar rich domains of the crenulation cleavage, representing the S_o fabric. The S_1 fabric is in turn crenulated by D2 and where D2 is more intense, for instance on Meallan Odhar, Pollgormack Hill and in the Tarff Gorge (Enclosure 1) the biotites are reorientated into a S_2 crenulation cleavage (Plate 3.2).

On the SE limb of the Corrieyairack Syncline, S_1 is the dominant fabric and it is not affected by F_2 crenulations. Here, the biotites still show two fabrics: one parallel to the dominant S_1 foliation and a second at an oblique angle to the bedding representing S_2 (Plate 3.3).

A weak cross-crenulation can be seen in semi-pelites from the Tarff Gorge, almost at right angles to the dominant S_2 fabric and as, in this case the individual mica laths are folded, it is thought that this is a D3 crenulation (Plate 3.4).

<u>Quartz</u> grains within the semi-pelites and pelites show a wide variation of size and shape. The quartz fabrics vary from an equidimensional granoblastic texture in association with plagioclase, to ribbon quartz with pronounced deformation bands and sutured grain boundaries. The equidimensional granoblastic texture is more common, occurring in the quartz and feldspar domains of the S_1 and S_2 crenulation cleavages within the Corrieyairack semi-pelites and also within all the Glenshirra Succession semi-pelites. The ribbon quartz occurs in rocks affected by intense D2 strains, as on Meallan Odhar (Enclosure 1).

The granoblastic texture of most of the quartz fabrics suggests

Plate 3.3 : Weak S_2 biotite fabric oblique to S_1/S_o biotite fabric (plane polarised light).

Plate 3.4 : Weak D3 crenulation of S_2 mica fabric. Knockchoilum Semi-psammite (crossed nicols).

Scale bar represents 0.1mm


S_1
S_2

that the rocks are approaching equilibrium and post tectonic recrystallization has removed the effects of any early deformation. However, within the mica rich domains of the semi-pelites, the micas and graphite, within the Corrieyairack Succession, have restricted grain growth and recrystallization so that early D1 or D2 deformation is recognisable as a fine-grained quartz fabric (Voll, 1960).

Plagioclase occurs in abundance throughout the semi-pelites making up as much as 40% of the rock (Table 3.2). Within the Glenshirra Succession and the Coire nan Laogh Semi-pelite, it varies in composition from An_{20} to An_{40} (oligoclase to andesine) and is generally well twinned with slight sericitic alteration.

Within the Glenshirra Succession the plagioclases are antiperthitic with patchy exsolution of alkali feldspar. Myrmekitic intergrowths between plagioclase and orthoclase also occur. Within the Corrieyairack Succession plagioclase compositions range from An_{10} to An_{36} (Michel-Levy method). Twinning is much less common and sericitic alteration more extensive than within the Glenshirra Succession. Antiperthitic plagioclase and myrmekitic intergrowths are absent.

Small 'drop-like' inclusions of quartz occur within plagioclase from both successions (Plate 3.5). The plagioclase also has twin boundaries with biotite (Plate 3.6) often with a concave biotite 'pushed aside' by the advancing less calcic plagioclase twin boundary. These features, together with the antiperthites have been attributed to the processes of grain boundary migration and impurity segregation (Byerly and Vogel, 1973) and are characteristic of annealed plagioclase from rocks of greenschist to middle amphibolite facies metamorphic grade. Impurity ions diffuse towards high energy areas of the plagioclase, particularly external boundaries but also internal sub-boundaries such as twin planes

Plate 3.5 : 'Drop-like' inclusions of quartz in plagioclase.
Allt Luaidhe Semi-psammite (crossed nicols).

Plate 3.6 : Twin boundary of plagioclase with biotite.
Allt Luaidhe Semi-psammite (crossed nicols).

Scale bar represents 0.1mm

or lattice defects. High grades of metamorphism increase diffusion rates and the effects of impurity segregation are therefore more pronounced.

Myrmekitic intergrowths occur at plagioclase, orthoclase boundaries only at or above middle amphibolite facies (Byerly and Vogel, op.cit.) although their origin has been the subject of much debate (Phillips,1974, 1980, Shelley,1964). An exsolution origin for myrmekites is advocated by Hubbard (1966) and Ashworth (1972, 1973), and Shelley (1964) suggests that this exsolution may be induced by deformation.

K-feldspar usually perthitic with very fine parallel perthitic stringers, occurs only within the Glenshirra Succession, within the quartz and feldspar rich domains of the semi-pelites. As discussed earlier, it forms myrmekitic boundaries with plagioclase. Individual grains are equidimensional and of similar grain size to the quartz and plagioclase.

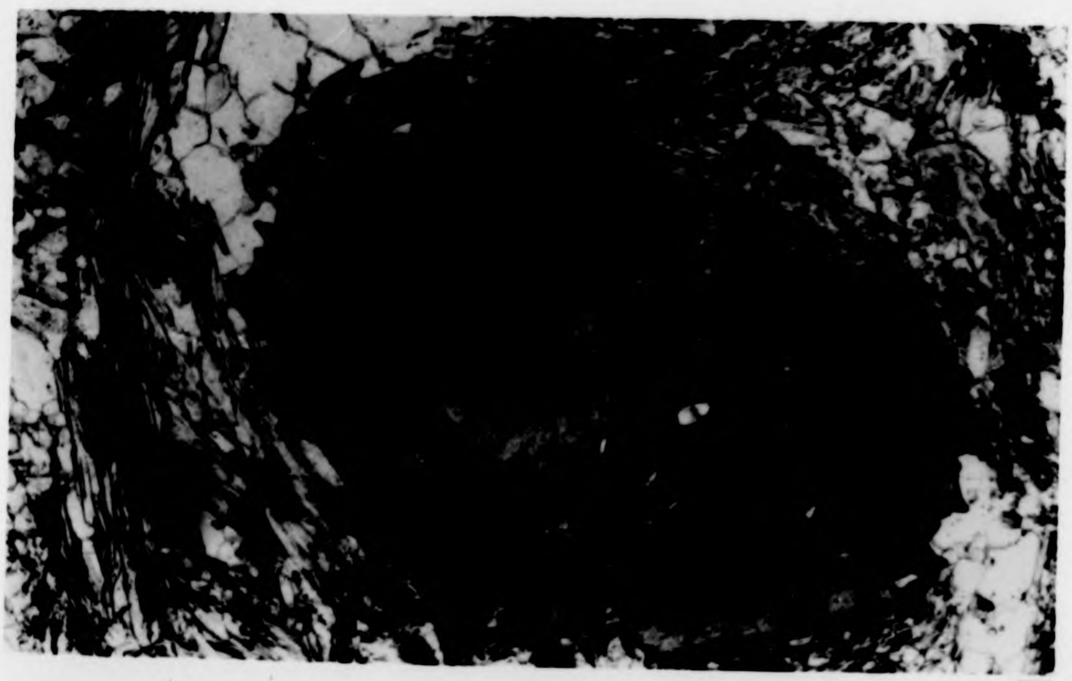
Garnet. Apart from a single occurrence within the semi-pelitic bands of the Allt Luaidhe Semi-psammite, garnet is restricted to semi-pelites from the Corrieyairack Succession, where it takes several forms and in many cases shows evidence of several stages of growth. Small rounded grains with a few inclusions of magnetite are enveloped by the S_1 biotite foliation and are probably syn-D1. These grains are often elongate parallel to S_2 suggesting that they were deformed during D2. Evidence that garnet growth also occurred during the development of S_2 is provided by spiral trails of small elongate quartz inclusions in garnet enveloped by S_2 (Plate 3.7). Some grains also have xenoblastic overgrowths indicative of two stages of growth (Plate 3.8).

The garnet generally shows some alteration to chlorite and often occurs as xenoblastic relict fragments, in association with randomly orientated muscovite, quartz, opaque, chlorite and biotite, with an

Plate 3.7 : Helicitic garnet showing syn-D1 growth lying within S_2 foliation (crossed nicols).

Plate 3.8 : Garnet showing evidence for two stages of growth lying within S_2 foliation. (plane polarised light)

Scale bar represents 0.1mm



envelope of strongly orientated biotite and chlorite laths.

Kyanite occurs in three of the semi-pelites examined, two from the pelitic units of the Creag Mhór Psammite(NN 481956) (Plate 3.9) and one from the Monadhliath Semi-pelite (NN 41259605). In each case it occurs as corroded laths, slightly cross-cutting the dominant S_1/S_o biotite fabric and shows alteration to sericite or muscovite.

Fibrolite is present in the same two semi-pelites from the Creag Mhor Psammite, 200m from the contact with the Corrieyairack Granodiorite. It occurs as fine randomly orientated needles nucleating on biotite and also in close association with muscovite (Plate 3.10).

Andalusite is present in one sample from the Monadhliath Semi-pelite, collected from within 1000m of the contact with the Corrieyairack Granodiorite. As with the fibrolite it is a product of contact metamorphism as a result of the intrusion. The andalusite occurs as large porphyroblasts up to 3mm in size of the chiastolite variety growing across the dominant S_1 foliation and F_2 crenulations (Plate 3.11).

Zircon is abundant within the Corrieyairack Succession but is less common within the Glenshirra Succession. It occurs as very small rounded grains poikiolitically enclosed by biotite, which has developed pleochroic haloes.

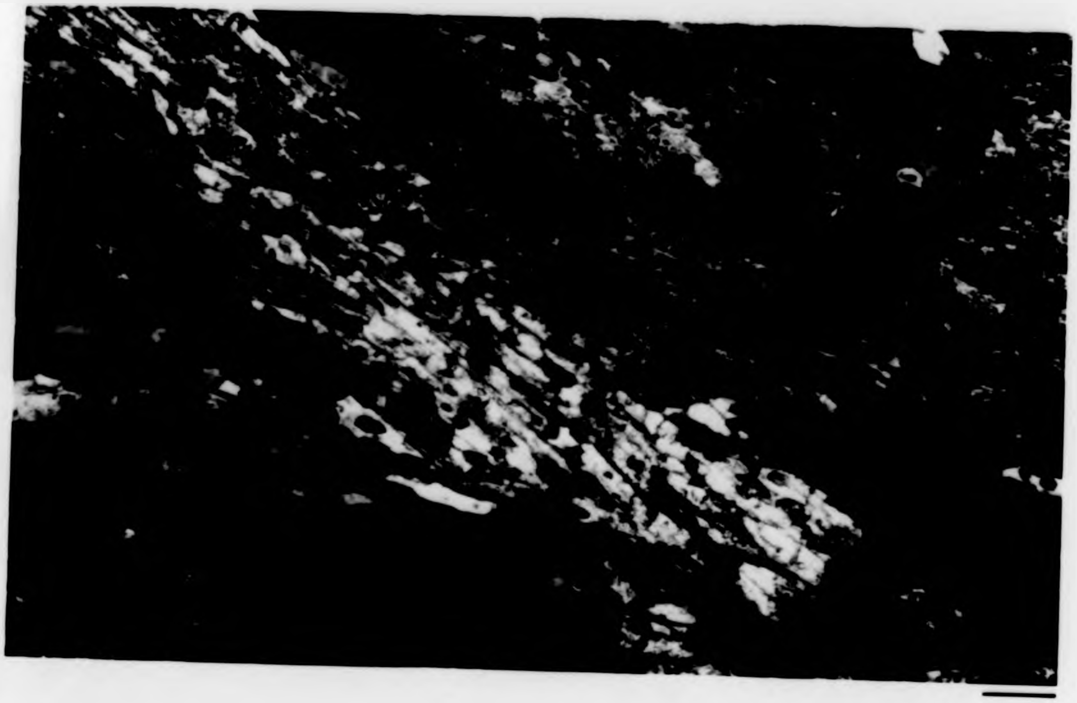
Apatite, epidote and sphene occur as small rounded grains within both the Corrieyairack and Glenshirra Successions, apatite being particularly common.

Small grains and laths of tourmaline also occur within the Coire nan Laogh Semi-pelite and Monadhliath Semi-pelite. Graphite is present within

Plate 3.9 : Laths of kyanite, slightly oblique to biotite defining the dominant S_1/S_o foliation from semi-pelite within Creag Mhór Psammite (NN 481956) (crossed nicols)

Plate 3.10 : Fibrolite growing across S_1/S_o biotite fabric, from semi-pelite within Creag Mhór Psammite adjacent to the Corrieyairack Granodiorite (NN 481956) (crossed nicols)

Scale bar represents 0.1mm



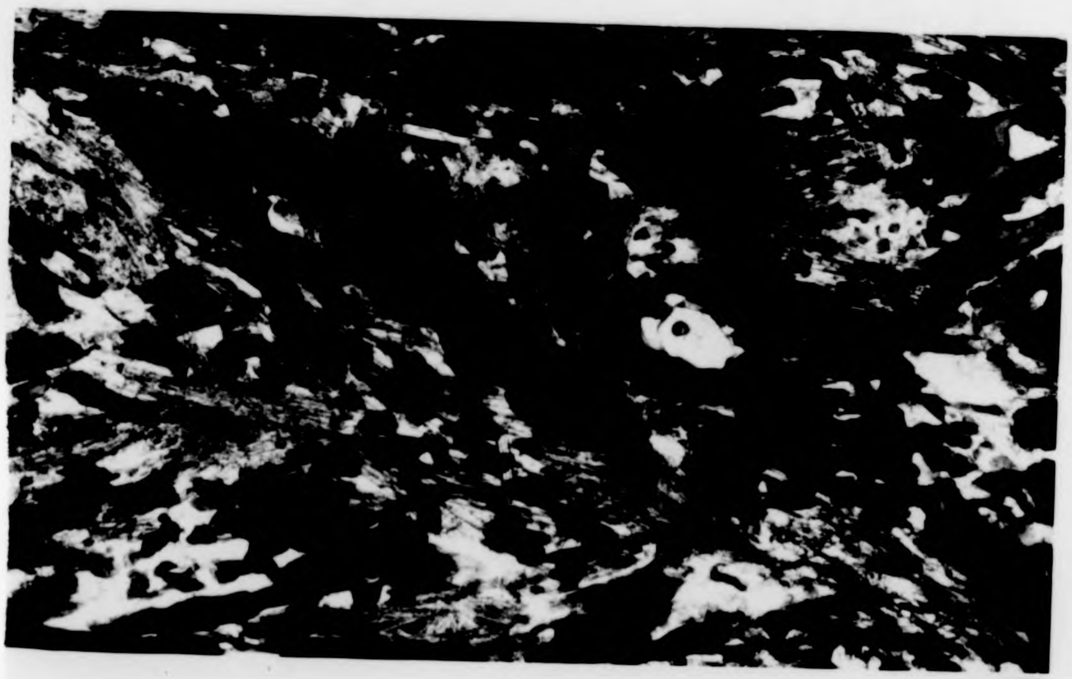
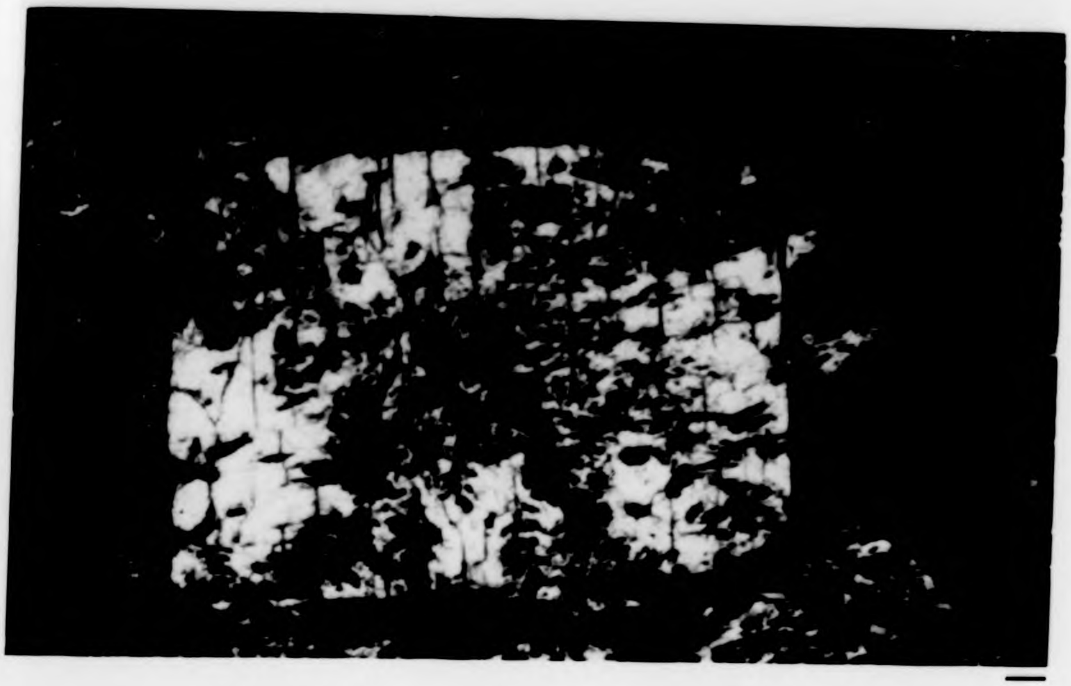
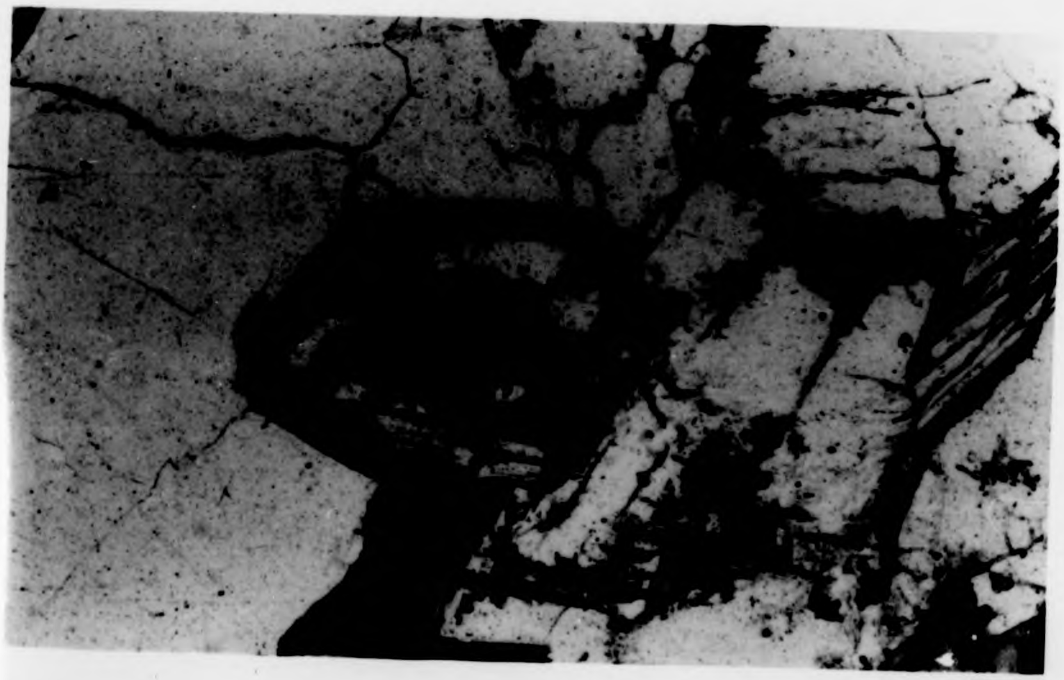


Plate 3.11 : Andalusite porphyroblasts, from pelite band from the Monadhliath Semi-pelite adjacent to the Corrieyairack Granodiorite (NH 41259605) (crossed nicols)

Plate 3.12 : Garnet from Coire nan Laogh Migmatitic Semi-pelite showing evidence for two stages of growth. (plane polarised light)

Scale bar represents 0.1mm





the semi-pelites of the Corrieyairack Succession as fine disseminated grains, distributed along mica grain boundaries and particularly concentrated along S_2 crenulation cleavage planes. Magnetite also occurs sporadically. The Glenshirra Succession contains in contrast irregular aggregates of haematite showing the characteristic red cleavage flakes.

a. Migmatitic Semi-pelite.

The basal 150 metres of the Coire nan Laogh Semi-pelite on Gairbeinn displays a coarser grained and more highly segregated fabric than the semi-pelitic bands from the other formations (Plate 2.2). This is thought to be a result of a variation in the local metamorphic conditions adjacent to the Gairbeinn Slide (Chapters 4 and 7).

The migmatitic semi-pelites have essentially the same mineralogy as the other semi-pelitic units, containing muscovite, biotite, quartz, plagioclase and garnet with apatite, tourmaline, chlorite, zircon and magnetite accessory minerals (see Table 3.3).

Biotite occurs as interlocking elongate laths, up to 3mm long, with a weak preferred orientation, and together with muscovite and garnet encloses lenticular areas of quartz and plagioclase. As with the remainder of the Corrieyairack Succession, the biotite is pleochroic from red-brown to pale brown and contains scattered inclusions of apatite and zircon, the latter surrounded by pleochroic haloes. A few smaller laths occur within the quartz and plagioclase rich zones, often orientated at high angles to the dominant foliation.

Muscovite occurs in close association with biotite as elongate laths up to 3mm long and generally contain no inclusions.

TABLE 3.3: MODAL ANALYSES OF 'MIGMATITIC' SEMI-PELITES AND QUARTZITES

Sample no.	107	244	281	39	311	101A
Quartz	28	23	32	84	92	74
Plagioclase	32	39	17	11	1	16
Biotite	27	19	28	-	2	.2
Muscovite	13	16	21	4	3	9
K-Feldspar	-	-	-	1	2	-
Garnet	1	2	.7	-	tr	-
Opaque	1	1	1	-	.2	1
Chlorite	tr	.3	-	-	tr	tr
Tourmaline	tr	tr	.2	-	-	-
Apatite	.6	.7	.7	-	-	tr
Zircon	tr	tr	tr	-	-	-
Total	102.6	101.0	100.6	100	100.2	100.2

107: Coire nan Laogh Semi-pelite
244: Coire nan Laogh Semi-pelite
281: Coire nan Laogh Semi-pelite
— 'Migmatitic' Semi-pelites

39: Monadhliath Semi-pelite
311: Monadhliath Semi-pelite
101A: Monadhliath Semi-pelite
— Quartzites

Garnet in present as rounded grains with very few inclusions, surrounded by an envelope of biotite, muscovite and opaques, and often shows some alteration to chlorite.

Textural evidence for more than one episode of garnet growth (Plate 3.12) is betrayed by the existence of rounded cores containing very few inclusions, indicative of fairly rapid growth, surrounded by a subhedral rim with abundant inclusions, which in most cases has been partially replaced by biotite, chlorite and opaques.

Some biotite laths are truncated by garnet porphyroblasts and this, together with enveloping mica, suggests that the garnet growth took place both prior to and during the formation of the dominant mica fabric.

Quartz shows a wide variation in grain size, between the mica rich zones and the leucocratic quartz and feldspar lenses. In the latter, quartz grains are roughly equidimensional, up to 2mm in diameter and often show strong undulose extinction and deformation bands (Plate 3.13) with irregular grain boundaries indicating the absence of strong post-tectonic annealing. Those quartz grains within the mica rich zones occur by contrast, as elongate grains with strong undulose extinction but also as grains made up of numerous subgrains, lacking undulose extinction,suggesting some post-tectonic re-equilibration.

Feldspar. Andesine (An_{30-38}) occurs as large rounded to irregular grains up to 2mm in diameter within the leucocratic lenses of the semi-pelite. Most grains show clear multiple Carlsbad/Albite twinning and very little sericitic alteration, although some grains are untwinned, or show irregular diffuse twins with patchy reverse zoning. Small rounded inclusions of quartz are common and contacts with biotite often show twin-like laminae of lower relief, less calcic plagioclase and distortion of

Plate 3.13 : Deformation bands in quartz grain from Coire nan Laogh Migmatitic Semi-pelite. (crossed nicols)

Scale bar represents 0.1mm

Plate 3.14 : Quartz and feldspar, and mica rich domains in Coire nan Laogh Migmatitic Semi-pelite. (crossed nicols)

Scale bar represents 1mm

the biotite (Plate 3.6). It has been suggested (Mehnert, 1968) that the drop-like inclusions of quartz are primary quartz relics and evidence for feldspathization or plagioclase blastisis. However, although considering the patchy nature of the plagioclase and albitic contacts with biotite, these may equally be a result of impurity segregation and grain boundary migration associated with amphibolite facies metamorphism as discussed in Section 2a (Byerly and Vogel, 1973).

Accessory Minerals: Apatite is abundant within the migmatitic semi-pelites and occurs as laths and rounded grains up to 1mm in size. Many of the grains are fractured and strung out along the biotite foliation possibly indicative of a phase of intense deformation affecting detrital apatite grains, prior to formation of the present foliation.

Tourmaline is present as scattered rounded grains as inclusions within garnet or within the quartz and feldspar lenses.

Opaques occur in close association with the mica rich layers. The laths have red translucent edges indicative of haematite but this may be a product of local oxidation of magnetite, either associated with the Gairbeinn Slide or due to weathering.

The migmatitic texture of the base of the Coire nan Laogh Semi-pelite is defined by trondhjemitic (Hatch, Wells & Wells, 1972), quartz and andesine, leucosomes surrounded by biotite, muscovite, opaque and garnet bearing melanosomes. The micas form polygonal aggregates around the convex lenses of the leucosome (Plate 3.14) indicating that mica crystallization took place after or contemporaneous with the growth of the leucosome. The dominant trend of the leucosome and the biotite fabric is parallel to the regional S_1/S_o foliation. Mehnert (1968) suggests that the main phase of migmatite formation normally takes place during deformation, when high mechanical mobility prevails, although the final stages of recrystallization will be post-tectonic. The deformation bands within the quartz of the leucosome are therefore thought to be due to the effects of later episodes of deformation and this model is supported by the development of a cross-crenulation of the dominant foliation associated with D2.

Yardley (1978) in his discussion of the origin of migmatites suggests that the trondhj emitic nature of the leucosome with little or no K-feldspar indicates an origin either by external metasomatism, with the addition of material from outside the system, or by internal metasomatism or metamorphic segregation without anatexis. He believes that much of the migmatization accompanying regional deformation is the result of metamorphic segregation (Robin, 1979) with the migmatitic rock or neosome having approximately the same composition as the paleosome or unaffected rock. Segregation is therefore essentially a hydrothermal process possibly initiated by hydraulic fracturing and devolatization reactions.

In this case it is considered that the Gairbeinn Slide and the deformation associated with it, created a zone along which the transport of the pore fluids necessary for the segregation process, is facilitated. This may be a result of early cataclasis as proposed by Tanner (1965) for the Rubha Ruadh semi-pelite associated with the Sgurr Beag Slide as well as or rather than the development of a pressure - temperature anomaly, as suggested by Ashworth (1976).

3. QUARTZITES

The term quartzite (sensu lato) was used in the field to describe massive white, cream or pink coloured highly siliceous rocks in which little or no mica can be seen, and which are readily distinguishable from psammites, although they contain up to 20% feldspar (see Table 3.1). These bands occur within and immediately below the Monadhliath Semi-pelite and also thin impersistent bands within the Coire nan Laogh Semi-pelite (see Chapter 2). They consist of quartz, plagioclase and muscovite with minor proportions of microcline, calcite, biotite, chlorite, apatite, sphene, opaques and garnet. Representative modal analyses are shown in Table 3.3.

Quartz occurs as equidimensional to elongate grains up to 2mm in length, and most grains have strong undulose extinction and internal deformation bands. In quartzites near the base of the Monadhliath Semi-pelite (GR.NH 40850080) the quartz fabric shows evidence of intense deformation. Sutured grain boundaries, a wide variation in grain size, including some extremely elongate grains, and the local formation of the subgrains, indicate a high strain environment and little of post tectonic annealing. (Fig. 3.15)

Elsewhere the quartz fabric is less deformed and the equidimensional to slightly elongate grains have curved boundaries, although grains rarely meet at triple points and still show strong undulose extinction indicative of non-equilibrium textures.

Feldspar. Plagioclase varies in composition from albite An_8 to andesine An_{36} and consists of elongate grains up to 0.5mm in length. The more calcic grains are usually well twinned with slight deformation of the twin lamellae. A few grains of microcline also occur, distinguished by the characteristic albite-pericline cross-hatch twinning.

Muscovite is the dominant mica present, occurring both as small laths along the grain boundaries of quartz and as large laths cross-cutting the foliation. These are closer to equidimensional and contain inclusions of quartz of ground mass size.

Biotite, generally partly altered to chlorite occurs sporadically as small laths, well-orientated parallel to the dominant S_1 foliation and displaying red-brown to pale yellow pleochroism.

Accessory minerals. Sphene, epidote, apatite and haematite occur as accessory minerals and are often concentrated in narrow bands in close association with muscovite, probably representing heavy mineral bands of sedimentary origin (Plate 3.16). Sphene occurs as irregular aggregates whilst apatite and epidote both occur as small rounded grains. Xenoblastic fragments of garnet were found in one sample. Finely disseminated haematite occurs as inclusions within plagioclase and also at quartz grain boundaries producing the pale pink colour of some of the quartzite bands.

Within quartzites of the Tarff Gorge a quartz-feldspar defined planar fabric was recognised in hand specimen and is deformed by crenulations axial planar to minor F_2 folds. In thin-section the quartz fabric approaches an equilibrium texture with curved boundaries and triple points suggesting that recrystallization and annealing of the S_1 fabric has occurred, possibly as a result of metamorphism associated with the second episode of deformation.

Elsewhere, particularly on Pollgormack Hill (NN 38909830) and in Allt Coire na Céire (NH 40950080) the quartzites retain their highly strained non-equilibrium texture and in this case the fabric is thought to have been established during the second episode of deformation, while subsequent metamorphism did not produce extensive recryatallization.

Plate 3.15 : Strongly deformed elongate quartz grains in quartzite from Monadhliath Semi-pelite. (crossed nicols)

Plate 3.16 : Heavy mineral band, composed of opaques, sphene, epidote and mica, in quartzite band from Monadhliath Semi-pelite. (plane polarised light)

Scale bar represents 0.1mm

These high-strain fabrics are thought to be a result of attenuation on the steep limbs of tight asymmetric F_2 folds (Chapter 7).

4. PSAMMITES AND SEMI-PSAMMITES

Psammites and semi-psammites are the dominant rock type within the metasediments of the Corrieyairack area. As well as making up the bulk of the semi-peammite and psammite formations, they also occur as thin ribs within the Monadhliath Semi-pelite and within the Coire nan Laogh Semi-pelite.

They have essentially the same mineralogy as the semi-pelites differing only in the proportion of mica to quartz and feldspar. Biotite, muscovite, quartz and plagioclase are essential constituents with minor variable proportions of garnet, calcite, alkali feldspar, chlorite, opaque, apatite, epidote tourmaline, zircon and kyanite. The results of modal analysis are given in Tables 3.4 & 3.5.

Rocks from the Glenshirra Succession can again be distinguished from those of the Corrieyairack Succession by the olive green / dark green colour of the biotite, the absence of garnet and the presence of alkali feldspar and associated myrmekititic intergrowths.

The biotites in the Glenshirra semi-psammites, in common with those from semi-pelites with the Glenshirra Succession, show evidence of two episodes of growth, with the development of numerous minute laths in optical continuity (Plate 3.1) with the non-poikiloblastic early growth. Again in common with the semi-pelites, these textures are best developed in the mica rich bands particularly those containing relict kyanite.

Plate 3.17 shows the relationship between biotite growth and the development of the S_1 and S_2 foliations. A coarsed-grained semi-pelitic band within the semi-psammite, representing S_o, the original bedding, is folded by an F_1 isoclinal fold. Biotite growth has occurred during D1

TABLE 3.4: MODAL ANALYSES OF PSAMMITES.

Sample no.	71	7870B	247	7868	9
Quartz	60	49	52	54	74
Plagioclase	30	34	16	22	11
K-Feldspar	4	-	18	19	-
Biotite	3	17	-	3	3
Muscovite	-	tr	12	.6	8
Calcite	-	-	-	-	3
Epidote	-	-	tr	-	-
Sphene	tr	tr	–	–	-
Opaque	.7	.3	.8	.3	-
Chlorite	2	-	-	.9	2
Apatite	tr	-	tr	–	–
Total	99.7	100.3	98.8	99.7	101

71: Creag Mhor Psammite
7870B: Creag Mhor Psammite
247: Allt Luaidhe Semi-psammite
7868: Creag Mhor Psammite

– Glenshirra Succession

9: Knockchoilum Semi-psammite. – Corrieyairack Succession

TABLE 3.5: MODAL ANALYSES OF SEMI-PSAMMITES.

Sample no.	113	106B	116	78	57	302	150	89	86	100
Quartz	26	25	21	11	44	34	48	40	27	30
Plagioclase	38	32	29	53	25	32	30	27	40	42
K-Feldspar	14	22	8	3	-	-	-	-	-	-
Biotite	6	15	27	28	13	12	11	22	16	18
Muscovite	4	3	12	tr	13	2	4	9	15	8
Garnet	-	-	-	-	.3	-	-	.6	-	.5
Calcite	-	-	-	-	2	20	6	-	.4	1
Epidote	5	.2	.1	.5	.6	-	-	-	-	-
Sphene	3	.2	-	tr	.3	tr	-	.5	.2	-
Opaque	2	2	2	3	.3	.2	.2	1	.2	tr
Chlorite	1	.2	-	tr	2	-	-	-	-	-
Apatite	-	.4	1	.4	tr	tr	.2	.4	tr	tr
Tourmaline	-	-	-	-	-	-	-	tr	tr	-
Zircon	-	-	tr	tr	.3	-	-	tr	-	-
Total	99	100	100.1	98.9	101	100.5	99.4	100	99.1	100

113: Gairbeinn Pebbly Semi-psammite
106B: Gairbeinn Pebbly Semi-psammite
116: Allt Luaidhe Semi-psammite
78: Allt Luaidhe Semi-psammite (Hornfels)

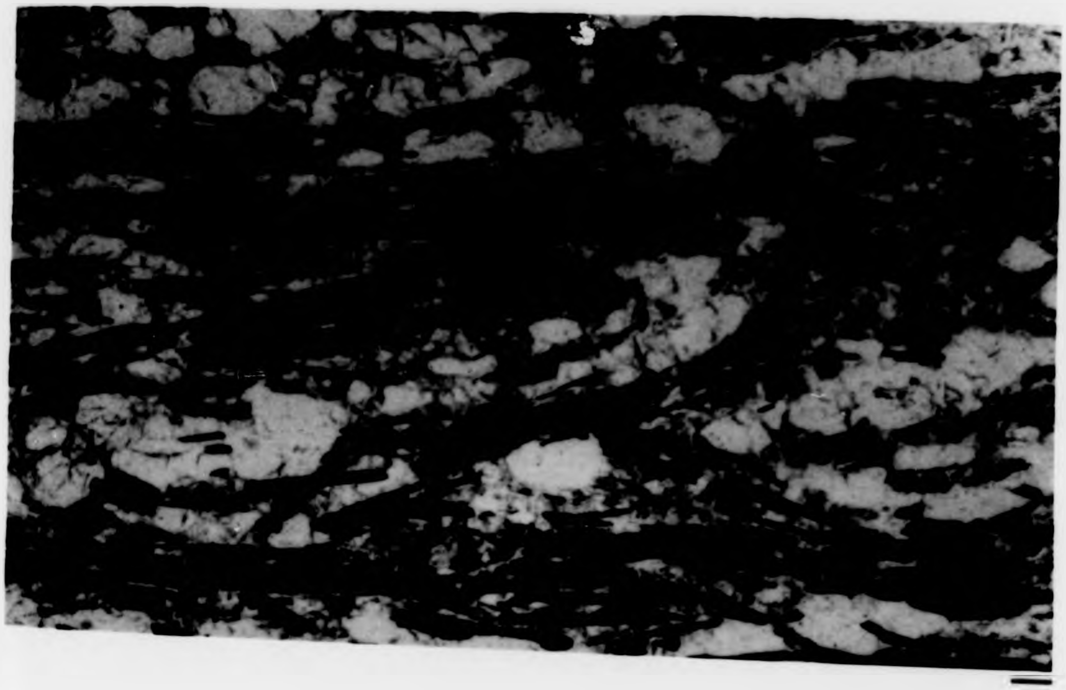
Glenshirra Succession

57: Monadhliath Semi-pelite
302: Carn Leac Semi-psammite
150: Carn Leac Semi-psammite
89: Knockchoilum Semi-psammite
86: Monadhliath Semi-pelite
100: Knockchoilum Semi-psammite

Corrieyairack Succession

Plate 3.17 : F_1 isoclinal fold of S_o (bedding) with some axial planar growth of biotite. S_2 biotite fabric developed at oblique angle to S_o/S_1 foliation. Psammite from Tarff Gorge. (plane polarised light)

Scale bar represents 0.1mm



and the laths are orientated parallel to the axial plane of the minor fold cross-cutting S_o only in the hinge zone of the fold. D2 has resulted in the development of a weak crenulation reflected in the orientation of biotite laths at high angles to the S_1 foliation.

Many of the semi-psammites and psammites within the Corrieyairack Succession contain substantial amounts of calcite. Usually these calcite bearing rocks occur as discrete pods or bands having sharp contacts with the non-calcite bearing semi-psammites. In these cases calcite comprises nearly 50% of the rock and is apparently an original constituent of the rock. These pods and bands are discussed together with the calc-silicate bearing pods and lenses in Chapters 5 & 6. However, the extensive calcite veining and irregular grains of calcite present in some semi-psammites, particularly those near the Sronlairig Fault, and in the Tarff Gorge, is thought to be of secondary origin. In these rocks the plagioclase shows extensive alteration to sericite and biotite and garnet are partially replaced by chlorite and calcite.

On the SE limb of the Corrieyairack Syncline the S_1 foliation is often poorly defined and the semi-psammites and psammites have a granoblastic, equigranular gabric generally finer than that of the foliated semi-psammites or semi-pelites, and only a weak preferred orientation of the biotites, which occur here as fairly well developed almost equidimensional non-poikiloblastic laths. The quartz grains have only a weak undulose extinction and grain boundaries are curved to straight, meeting at triple points. This equilibrium texture is present in most of the semi-psammites on the NW limb of the Corrieyairack Syncline on Carn a Chuilinn (NH 41400346). However, within the semi-psammite and psammitic ribs of the Monadhliath Semi-pelite on the NW limb of the syncline, the quartz grains are elongate and display strong undulose extinction and sutured grain boundaries, while the micas show a strong preferred orientation. This texture is consistent with the increase in the intensity of D2 towards the northwest, described in Chapter 7, also seen in the quartzites and semi-pelite lithologies of this area.

a. Gairbeinn Pebbly Semi-psammite.

The Gairbeinn Semi-psammites have essentially the same mineralogy as the other metasediments, but the numerous clastic fragments, and the effects of intense deformation serve to distinguish the formation from the rest of the semi-psammites from either succession.

The clastic fragments or pebbles are predominantly composed of quartz aggregates, possibly representing original quartz pebbles, in which the quartz grains reach 1mm in diameter and have strong undulose extinction and sutured boundaries (Plate 3.18). Aggregates of fine grained quartz and plagioclase also occur with small muscovite laths along grain boundaries and also coarser aggregates of microcline (Plate 3.19) and quartz and plagioclase. The plagioclase contain small drop-like quartz inclusions. The pebbles are difficult to distinguish from the quartz rich domains of the semi-psammite matrix particularly where they are highly deformed at the top of the formation; however the ubiquitous mica envelope surrounding lenticular areas with a grain size and fabric contrasting with the matrix suggests the presence of lithic clastic fragments.

The matrix of the formation consists of alternations of mica rich layers and quartz rich layers. These are considered to be the original lithological variation as at the less deformed base of the formation, thin graded units can be recognised (Chapters 2 & 5). These have a gradual upward increase in mica content followed by a sharp break, overlain by a more quartz rich layer. Scattered clastic fragments occur within both the

Plate 3.18 : Aggregates of fine grained quartz and feldspar surrounded by thin envelopes of mica, representing original clastic fragments in Gairbeinn Pebbly Semi-psammite. (crossed nicols)

Scale bar represents 5mm

Plate 3.19 : Microcline aggregates representing original clastic fragments in Gairbeinn Pebbly Semi-psammite. (crossed nicols)

Scale bar represents 0.1mm

quartz rich layers and the semi-pelitic layers although they are less frequent in the latter.

Biotite is the dominant mica, and consistent with the remainder of the Glenshirra Succession, is dark green to olive green in colour. It also shows evidence of two stages of growth, with non-poikiloblastic laths surrounded by minute laths in optical continuity. Muscovite occurs as elongate laths, assocated with biotite and as large cross-cutting porphyroblasts. The high relief, pale brown colour and low 2V suggest a high paragonite component. Some of the laths have strong undulose extinction and contain kink bands thought to be a result of late deformation.

In contrast to the other metasediments, the mica rich bands contain abundant grains of epidote up to 0.5mm in diameter and also aggregates and scattered grains of sphene, associated with abundant irregular grains of ilmenite or magnetite. The epidote occurs both as large rounded grains and as tiny fragments strung out along the foliation and it is considered that these minerals represent original detrital grains.

In contrast to the remainder of the Glenshirra Succession, garnet occurs within the the mica rich layers as subidioblastic to xenoblastic grains. The idioblastic grains overgrow the mica fabric, but small rounded grains with fine quartz inclusions occur surrounded by mica envelopes and some grains are elongate within the plane of S_1, suggesting that they were either formed early during M_1 or are of detrital origin. Much of the garnet has been affected by alteration to biotite, muscovite and chlorite.

Quartz occurs within the mica rich domains as small elongate grains divided into subgrains, but within the quartz rich domains the quartz grains reach 1mm in diameter and have strong undulose extinction, deformation bands and irregular grain boundaries with the development of subgrains at the grain boundaries.

Microcline is a common constituent of the semi-psammites as scattered grains approximately 0.5mm in diameter, as well as in aggregates with quartz in the pebbles.

Plagioclase varies from An_{30} to An_{39} and often has patchy exsolution of microcline and quartz and myrmekitic boundaries, as described from the semi-pelites and semi-psammites from the remainder of the Glenshirra Succession.

The variety of minerals within the Gairbeinn Semi-psammite is taken to indicate the immature nature of the original sediment and is discussed in further detail in Chapter 5. The fabrics and textures present in samples from near the top of the formation are also a result of intense deformation associated with the Gairbeinn Slide (Chapter 7). This has resulted in the elongation and flattening of the clastic fragments, but the strongly sheared fabric has been annealed by subsequent metamorphism producing a blastomylonitic fabric. The fine grained quartz, retained particularly where micas have restricted recrystallization are evidence for an early mylonitic fabric as are the strong undulose extinction with subgrains and sutured boundaries of quartz and the disrupted detrital epidote grains.

There are therefore several differences in petrology between rocks from the two succession in the Corrieyairack Pass area. The Corrieyairack Succession is characterised by red-brown biotite and the presence of graphite, magnetite and garnet, whilst the Glenshirra Succession is characterised by green biotite, the absence of graphite and garnet but the presence of haematite and K-feldspar. Rocks from the two successions can therefore generally be distinguished in thin section.

CHAPTER 4 : GEOCHEMISTRY OF THE METASEDIMENTS

1. INTRODUCTION

One hundred and sixty six samples of the metasediments from the Corrieyairack area have been analysed by X-ray Fluorescence and wet chemical techniques, for eleven major and eight trace elements. (Details of analytical techniques and sample preparation can be found in Appendix A, and full list of analyses and sample locations in Appendix B.) Amphibolites and the other igneous rocks in the area were also sampled but are discussed in Chapter 8.

The geochemistry of the metasediments was studied to investigate
1. the original nature of the sediments and the factors which have contributed to their composition including, the nature of the source rock, conditions of weathering, their depositional environment and
2. the effects of subsequent diagenesis and metamorphism.
It was hoped to be able to characterise the two metasedimentary successions and individual formations geochemically, as an aid to their recognition and correlation outside the Corrieyairack area.

The samples were selected to include the full range of rock types present in the two successions, but the geochemistry of the calc-silicate and calcite and calcite bearing pods and lenses is discussed with reference to the metamorphic history (Chapter 6). As the Glenshirra Succession occupies less than one quarter of the total area mapped, the sample numbers have a strong bias in favour of the Corrieyairack Succession (89 samples cf. 28). Sampling was also biased in favour of semi-pelitic lithologies, as these were considered to be the most informative both mineralogically (Chapter 3) and geochemically, due to the diluting effect of SiO_2 in psammitic lithologies. The restricted occurrence of semi-pelites within the Glenshirra Succession also accounts for the strong bias in sample numbers in favour of the Corrieyairack Succession and the

Glenshirra Succession is represented by analyses in the higher part of the SiO_2 range. This is an important factor which must be taken into consideration when comparing the chemistry of the two successions , (Section 3).

2. WHOLE ROCK CHEMISTRY

a. Variation within Rock Type and Range of Composition.

The metasediments were divided in the field into five main rock types, subsequently defined by modal analysis, on the basis of the relative proportions of quartz, feldspar and mica (Chapter 3). SiO_2 is the major chemical variable between rock types, but due to the slightly subjective nature of the subdivision the ranges of SiO_2 for each rock type show considerable overlap (Fig 4.1, Table 4.1). The particularly large overlap in SiO_2 between semi-pelites and semi-psammites is also due to variations in the proportion of feldspar in the semi-psammites (Chapter 3), a high feldspar content lowering the SiO_2 concentration.

Table 4.1

	No. of Samples	SiO_2 Mean		Range (%)
PELITES	2	49.15	1.12	< 50
SEMI-PELITES	55	59.4	4.6	50 - 66.2
SEMI-PSAMMITES	48	67.48	4.49	54.8 - 77.1
PSAMMITES	11	77.7	3.4	72.8 - 84.4
QUARTZITE	1	90.6	-	> 90

With the exception of Nb and Na_2O, all the major and trace elements show a negative correlation with SiO_2, particularly TiO_2, Al_2O_3, FeO, MgO, P_2O_5 and Cr (correlation coefficients <-0.7)(Figs 4.2-4.5) K_2O, Rb, Fe_2O_3, Y, Ni, Ba and MnO show slight negative correlations (correlation coefficients -0.46 to -0.68) but CaO, Sr, Zr, Nb and Na_2O show poor correlations with a wide scatter of points. These negative correlations are an effect of 'closure' due to the constant sum of geochemical data,

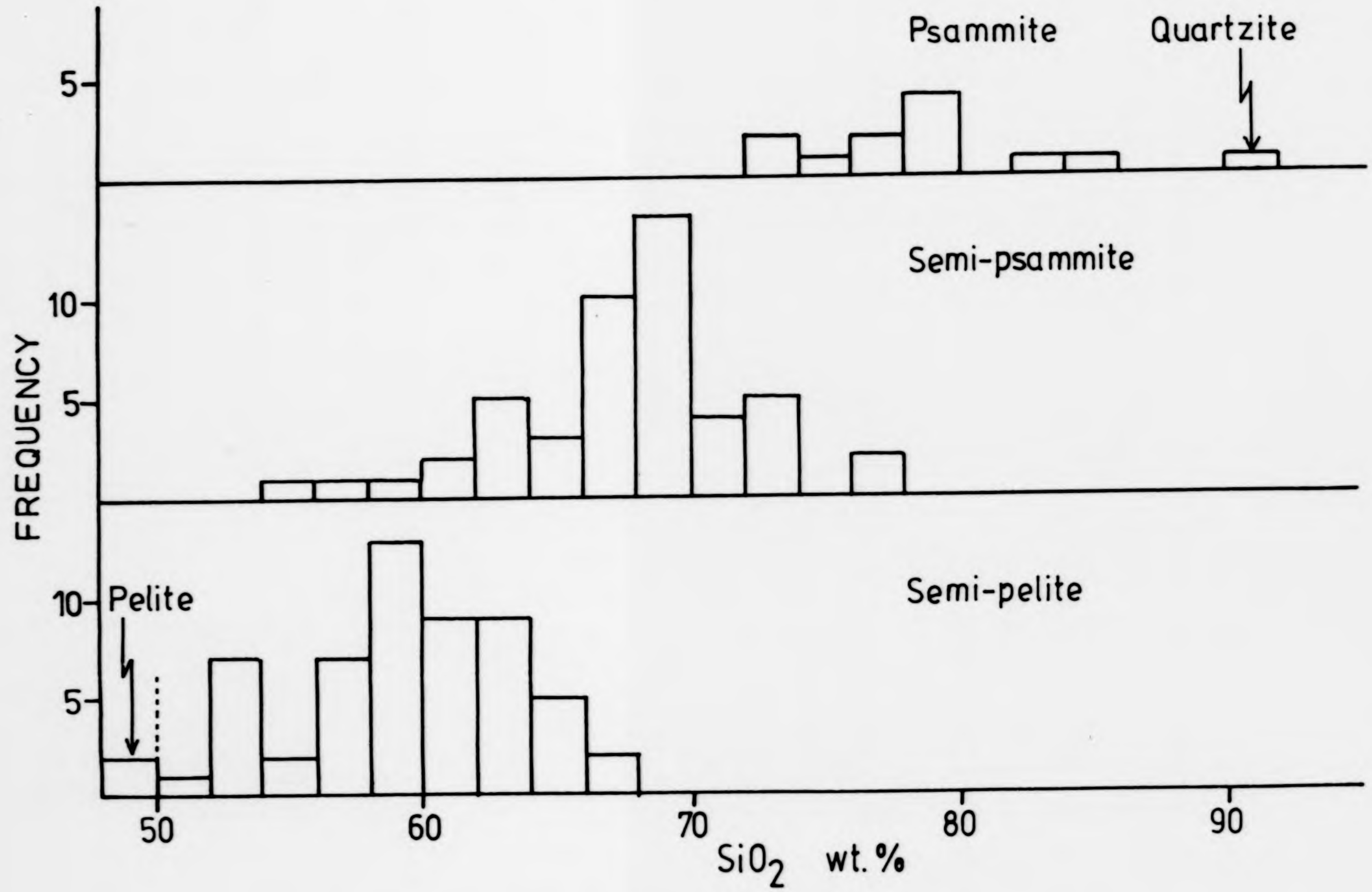


Figure 4.1: Histograms of SiO_2 wt. %. for the five rock types.

(Section 4) (Skala, 1979). This problem produces the diluting effect of quartz or SiO_2 in the more psammitic lithologies, therefore in the following comparisons of both the two successions and individual formations, each rock type is considered separately.

Quartzites occur only within and immediately below the Monadhliath Semi-pelite (Chapter 2). Because of their restricted mineralogy, they were considered to be relatively unimformative; hence a single sample (101A) is included solely for comparative purposes.

Sample 101A (Table 4.2) approximates in composition to a subarkose or protoarkose, with higher Al_2O_3 than the average orthoquartzite , (Pettijohn, 1963) indicating the presence of a proportion of feldspar or clay minerals, in the original sediment. The low values for most trace elements in the sample, particularly Zr, Cr and Ni, point to the lack of heavy minerals, often characteristic of well washed quartzites or protoquartzites (Pettijohn, 1963, Krauskopf,1967).

b. Variation between Successions.

The Corrieyairack and Glenshirra Successions (Chapter 2) show many chemical differences that can be recognised by comparison of the means for each rock type (Table 4.3) and by examination of selected variation diagrams, on which the two successions plot in separate fields (Figs 4.2-7)

The Gairbeinn Pebbly Semi-psammite is chemically distinct from the remainder of the metasediments and plots separately on most variation diagrams. In view of the unusual chemical and sedimentological character of this formation (Chapters 2 & 4), analyses from the Gairbeinn Pebbly Semi-psammite are not included in means of the Glenshirra Succession

TABLE 4.2

	A	B	C	D	s.d.	E	s.d.
SiO_2	90.65	95.4	92.91	89.21	7.11	92.39	5.20
TiO_2	.06	.2	–	.26	.22	.19	.16
Al_2O_3	4.16	1.1	3.78	5.70	3.67	4.23	3.00
Fe_2O_3	.29	.4	tr	–	–	–	–
FeO	.15	.2	.91	.76*	.64*	.52*	.40*
MnO	.04	-	-	.01	.01	.01	.01
MgO	.29	.1	tr	.25	.24	.21	.33
CaO	.48	1.6	.31	.60	1.27	.19	.35
Na_2O	1.65	.1	.34	1.16	1.36	.50	.68
K_2O	.66	.2	.61	2.03	1.45	1.75	1.21
P_2O_5	.04	-	-	.03	.08	.01	.01
L.O.I.	.69	1.4	1.19	–	–	–	-
Total	99.16	100.7	100.05	100.01		100.00	
Rb	16			52	36	49	31
Sr	97			53	44	26	19
Ba	346			493	296	515	239
Ni	14						
Y	4			11	7	10	9
Cr	10						
Zr	104			341	322	314	298
Nb	38			7	12	4	3

*Total Fe as FeO   s.d.= standard deviation

A Quartzite from Monadhliath Semi-pelite (PJH 101A)

B Mean Ortho-quartzite (Pettijohn, 1963, Table 12)

C Proto-quartzite (Pettijohn, 1963, Table 4)

D Mean of 43 analyses of Eilde Quartzite (Hickman, 1972)

E Mean of 36 analyses of Glen Coe Quartzite (Hickman, 1972)

ANALYSES OF QUARTZITES.

TABLE 4.3

	A		B		C		D		E	F	
SiO_2	60.46	3.72	54.47	2.95	67.91	4.15	66.85	6.30	77.93	78.80	3.77
TiO_2	.87	.14	1.15	.24	.64	.14	.68	.15	.27	.33	.11
Al_2O_3	17.53	1.89	18.97	1.10	14.05	1.84	15.31	2.54	8.72	10.63	1.66
Fe_2O_3	1.96	1.44	3.73	1.21	.98	.41	1.51	.57	.25	.82	.67
FeO	4.55	1.58	5.29	2.14	3.45	.96	2.30	1.31	1.37	1.11	.47
MnO	.14	.06	.17	.04	.12	.06	.09	.01	.06	.05	.03
MgO	2.46	.55	3.18	.90	1.88	.65	1.36	.98	.56	.79	.88
CaO	2.28	.77	1.67	1.15	2.39	1.13	1.36	.68	2.07	1.04	.34
Na_2O	3.14	.96	2.18	1.49	3.42	.61	3.34	1.24	3.39	2.80	.52
K_2O	3.31	1.23	6.14	1.92	2.36	.96	4.71	1.44	.99	3.49	.93
P_2O_5	.28	.11	.28	.06	.20	.10	.17	.11	.06	.06	.03
Rb	140	36	229	97	98	34	121	45	28	95	27
Sr	322	89	281	249	343	77	331	153	252	228	38
Ba	877	309	1214	144	631	252	1202	486	335	862	129
Ni	35	9	61	25	28	7	22	11	15	28	28
Y	35	9	37	12	26	6	20	9	13	13	6
Cr	60	12	85	19	39	8	32	20	19	19	4
Zr	223	72	312	193	248	106	258	119	220	182	108
Nb	25	5	21	5	24	5	24	9	24	29	7

A Mean of Corrieyairack semi-pelites (49 analyses)

B Mean of Glenshirra semi-pelites (7 analyses)

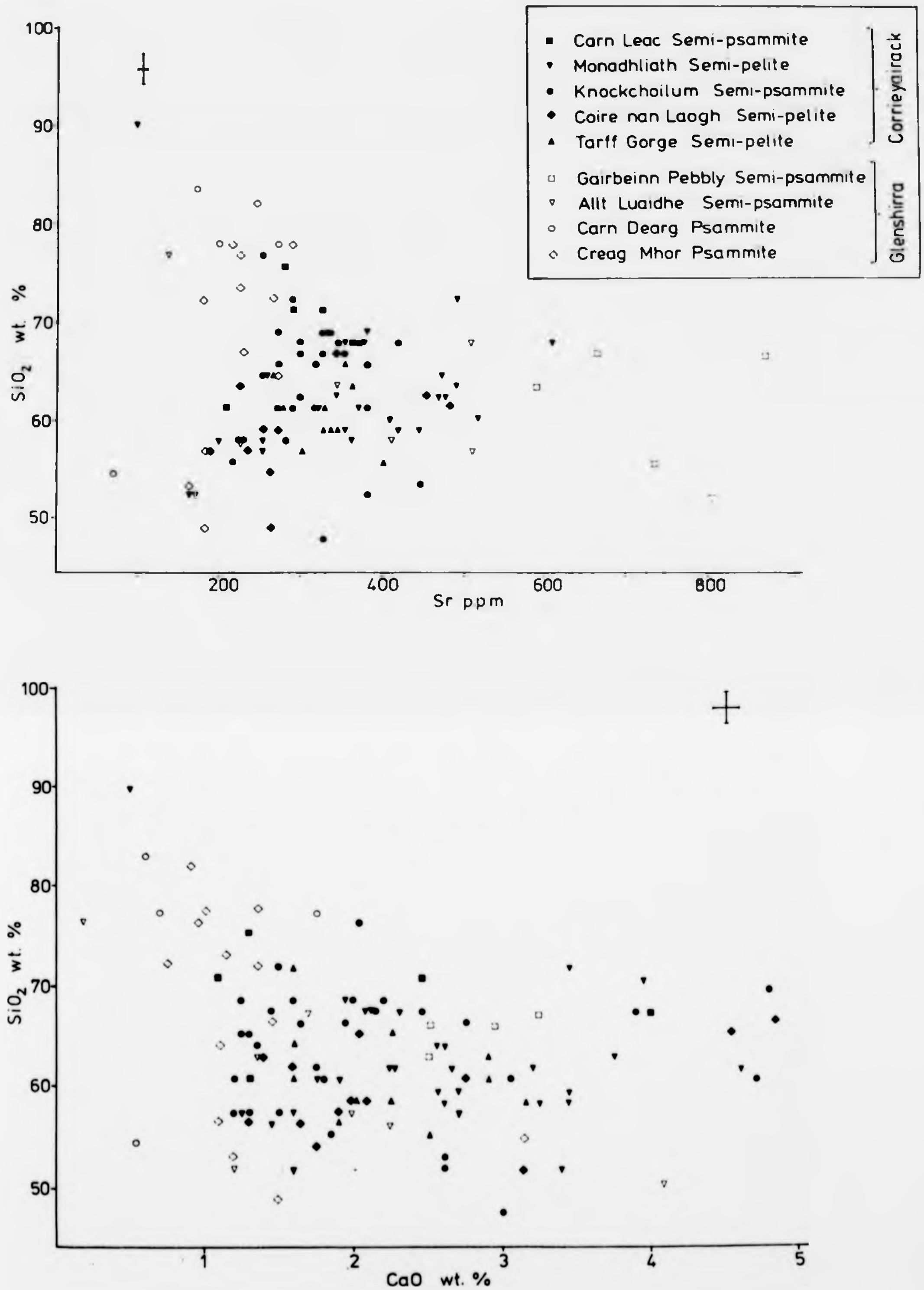
C Mean of Corrieyairack semi-psammites (37 analyses)

D Mean of Glenshirra semi-psammites (6 analyses)

E Corrieyairack psammite (Sample no. PJH 126)

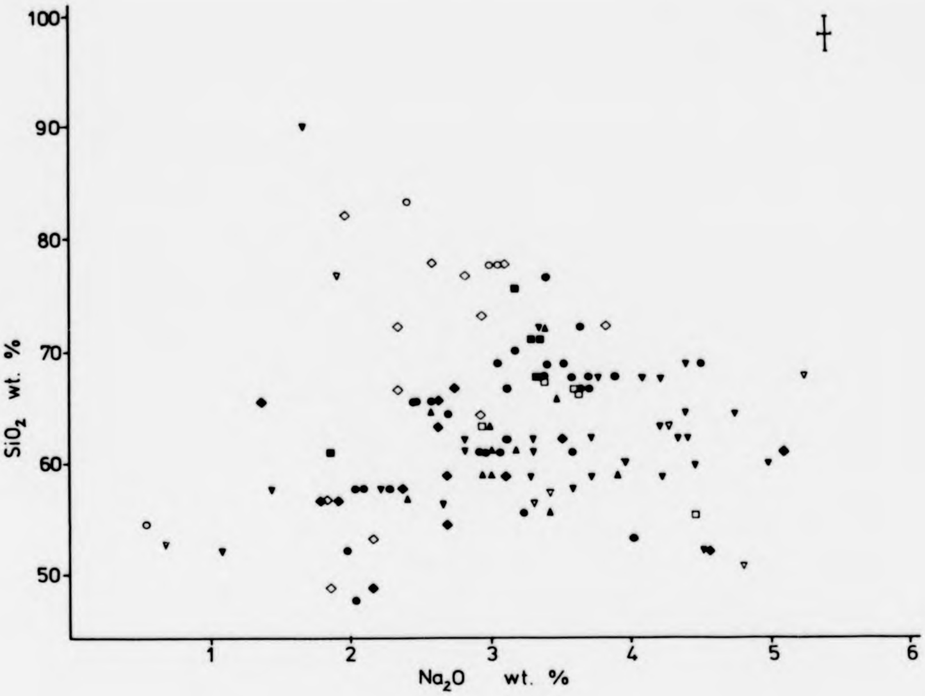
F Mean of Glenshirra psammites (10 analyses)

COMPARISON OF MEANS OF THE TWO SUCCESSIONS.



Carn Leac Semi-psammite
Monadhliath Semi-pelite
Knockchoilum Semi-psammite
Coire nan Laogh Semi-pelite
Tarff Gorge Semi-pelite
Corrieyairack
Gairbeinn Pebbly Semi-psammite
Allt Luaidhe Semi-psammite
Carn Dearg Psammite
Creag Mhor Psammite
Glenshirra
SiO_2 wt. %
Sr ppm
200
400
600
800
100
90
80
70
60
50
CaO wt. %
1
2
3
4
5

Figure 4.2.



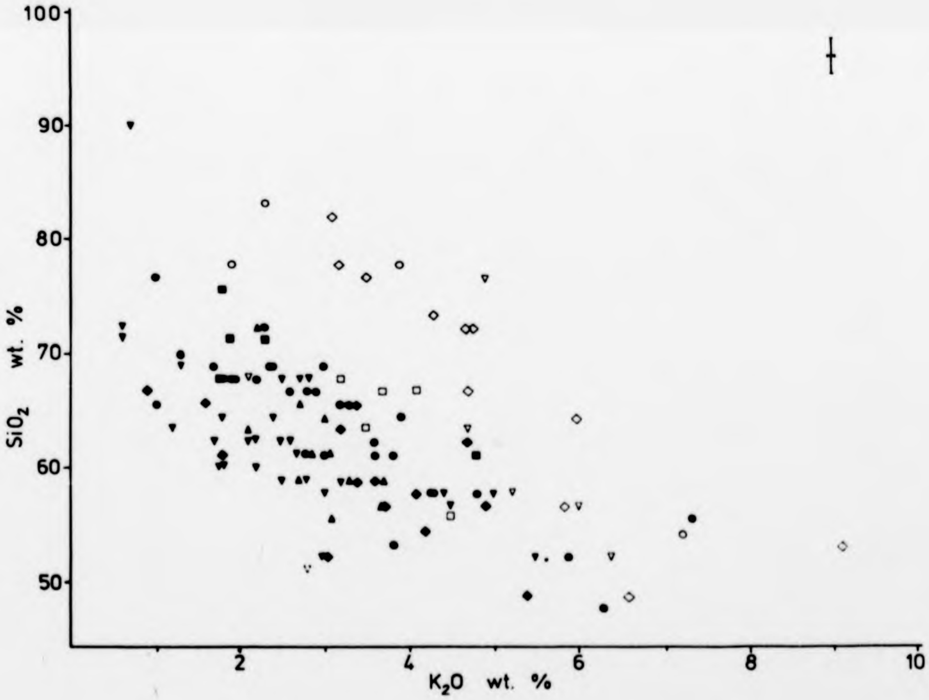
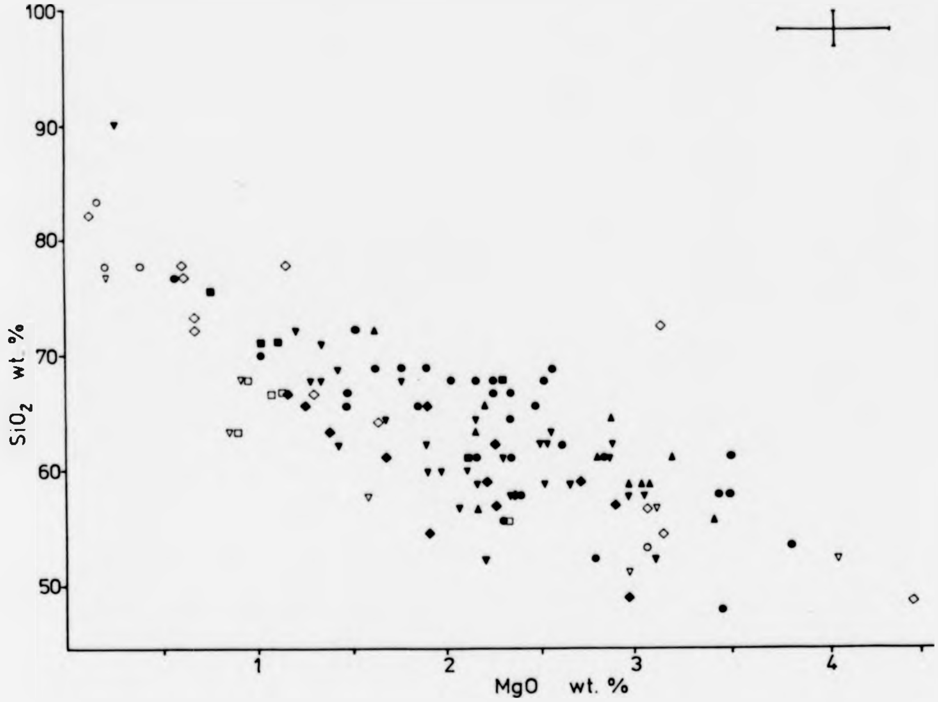


Figure 4.3: (Key as for figure 4.2).



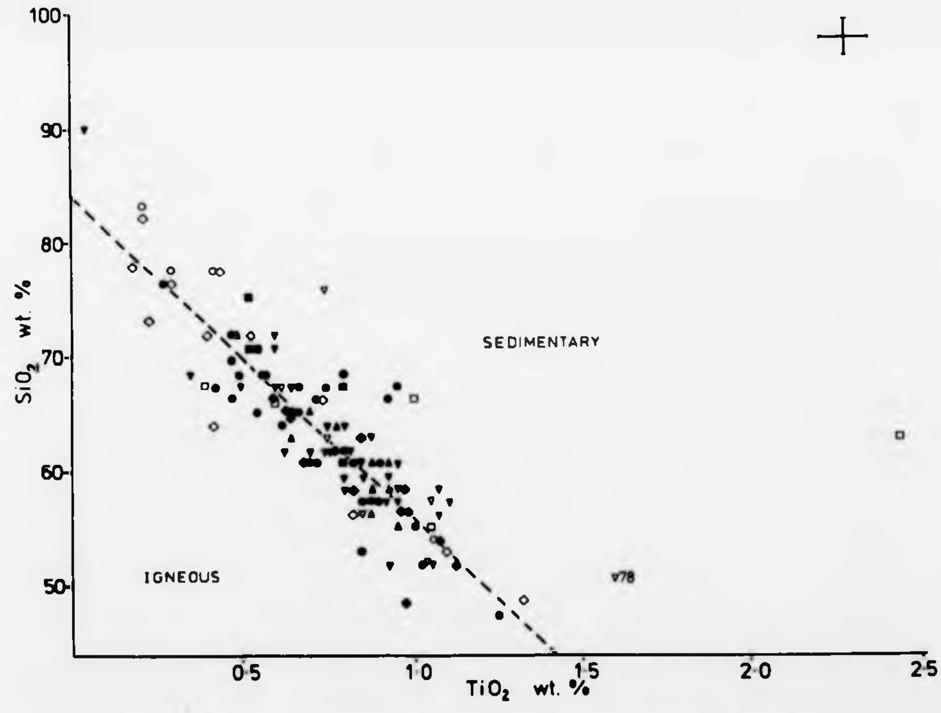
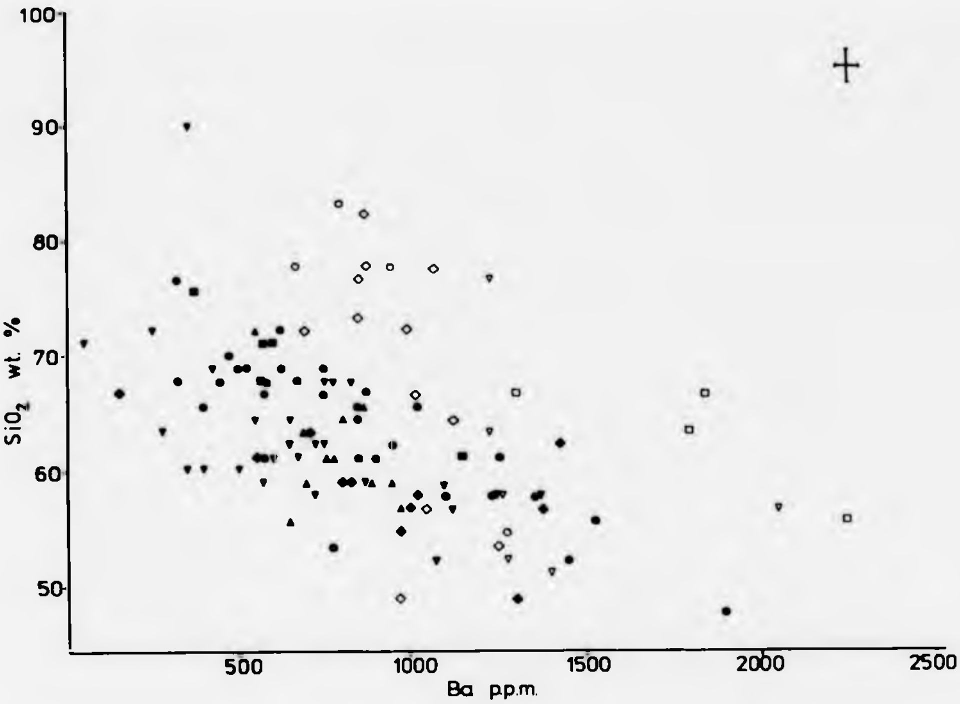


Figure 4.4: a) SiO_2 v. MgO b) SiO_2 v. TiO_2 after Tarney (1977).

(Key as for figure 4.2).



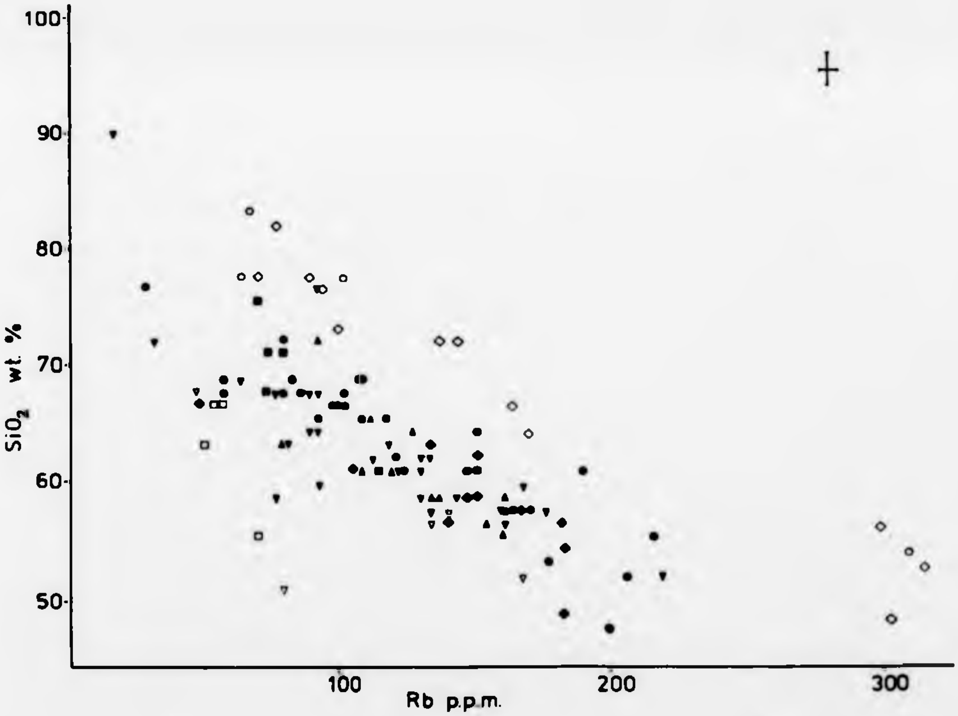


Figure 4.5: (Key as for figure 4.2).

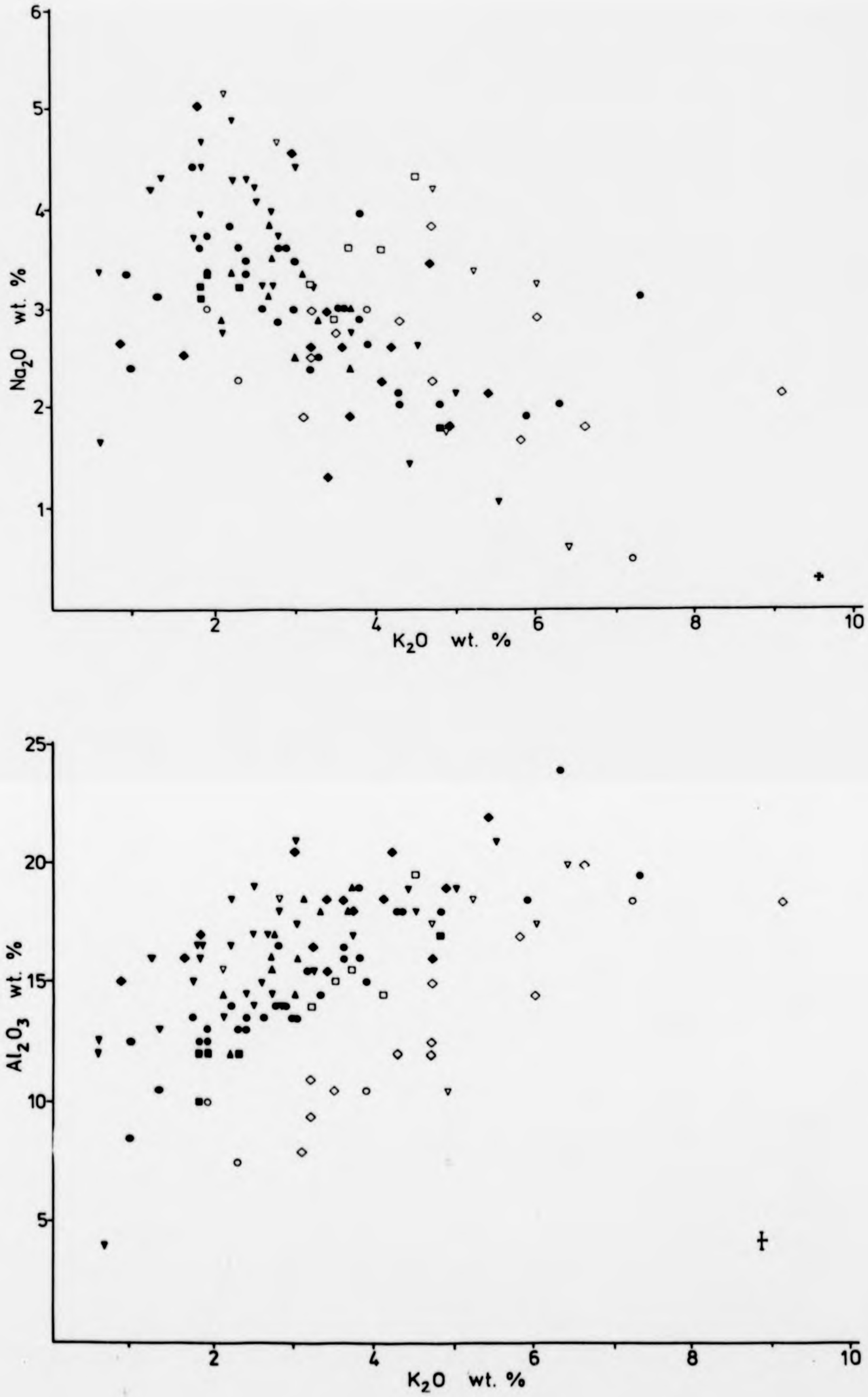
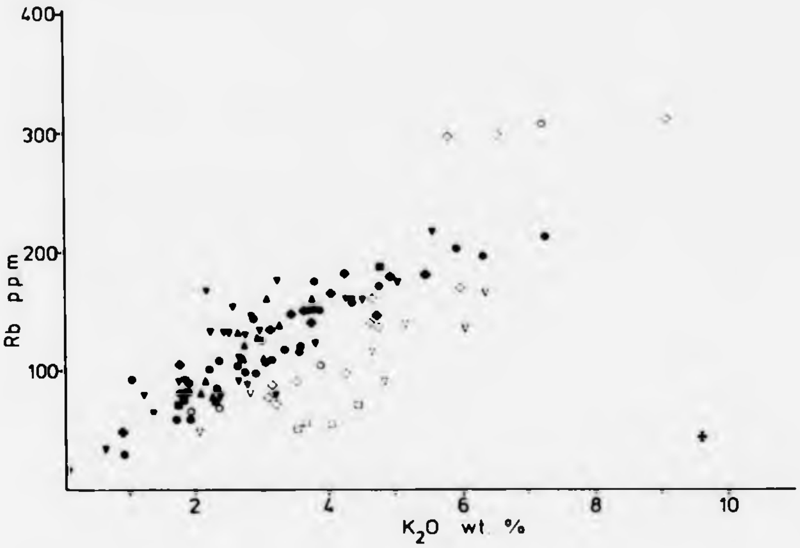


Figure 4.6: (Key as for figure 4.2).



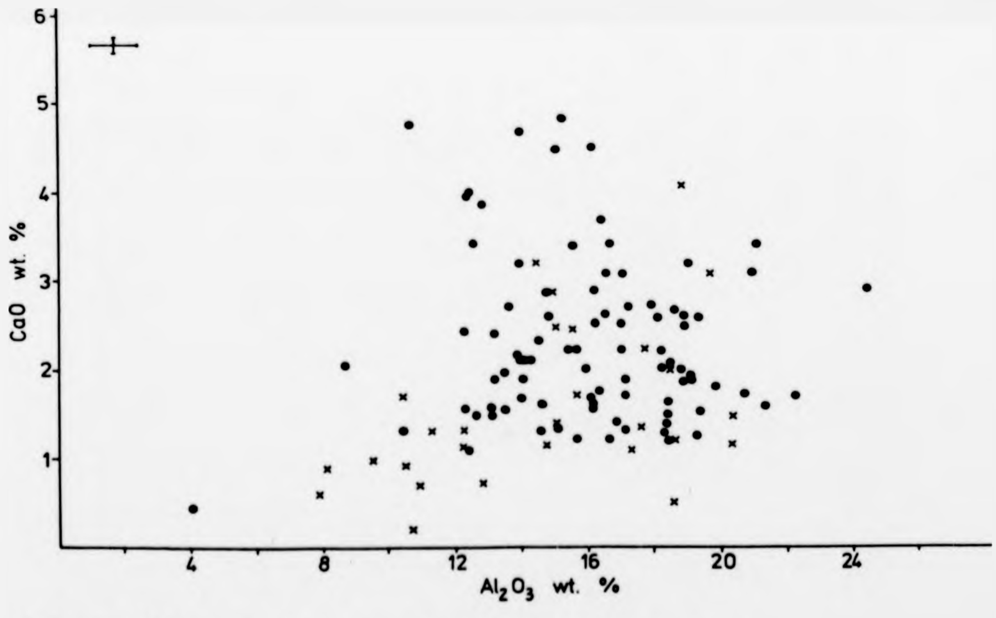


Figure 4.7: a) Rb v. K_2O (Key as for figure 4.2).

b) CaO v. Al_2O_3 Corrieyairack Succession (•), Glenshirra Succession (×).

(Table 4.3), but will be discussed with reference to variations between the individual formations.

i. Semi-pelites.

As already shown (Section 2a), the semi-pelitic lithologies contain the highest concentrations of most elements and the analyses are therefore considered to be more reliable and show the differences between the successions more clearly. However, the small number of samples for the Glenshirra Succession may mean that the mean and standard deviations calculated are not completely representative, and this must be remembered when comparing the two successions.

The Glenshirra semi-pelites have higher concentrations of FeO, Fe_2O_3, MnO, MgO, K_2O, Rb, Ba, Ni and Cr than the Corrieyairack semi-pelites and lower concentrations of CaO, Na_2O and Sr. The average SiO_2 is lower for the Glenshirra semi-pelites and this difference probably largely accounts for the differences in Al_2O_3 and total Fe.

ii. Semi-psammites.

The Glenshirra semi-psammites similarly have higher Fe_2O_3, K_2O, MgO, Ba and Rb, but FeO and CaO are lower than in the Corrieyairack semi-psammites (Table 4.3). The differences in oxidation state of the Fe between rock types may be due to the smaller amount of mica with high Fe^{2+} in the semi-psammites compared with the semi-pelites or possibly a more oxidising environment in the original sediment of the semi-psammites. In both rock types the Fe_2O_3/FeO ratio is higher in the Glenshirra rocks than in those of the Corrieyairack.

iii. Psammites.

Comparison of the single psammite analysis from the Corrieyairack Succession with the ten samples from the Glenshirra succession reveals that the higher values for Fe_2O_3, K_2O, Rb and Ba are consistent throughout the three rock types, and these differences can be clearly demonstrated on plots of Rb, Ba and K_2O against SiO_2 (Figs 4.3-4.5) The Glenshirra psammites also have lower concentrations of CaO and Na_2O, but due to the large scatter of values, this is less clear on the variation diagrams (Figs 4.2 and 4.3).

The differences between the two successions are emphasised by comparison of the ratios between various elements. The two successions can be differentated on a plot of K_2O against Al_2O_3, where the Glenshirra Succession has a higher value of K_2O/Al_2O_3 for all rock types (Fig 4.6b). The Glenshirra Succession also has higher values for K_2O/Na_2O, MgO/CaO and K_2O/Rb (Fig 4.7a) but lower values for CaO/Al_2O_3 and Sr/Rb (Fig 4.7 & 4.8).

c. <u>Discussion of the Variations between Successions.</u>

The geochemistry of the metasediments is determined partly by the nature of the source rock and physical conditions of deposition, and partly by the effects of subsequent metamorphism and metasomatism. The latter chemical shanges must be assessed before the variations between the two successions can be related to differences in the original nature of the sediments.

Many workers in the Moine and elsewhere (Shaw,1954,1956, Butler,1965, Haynes,1969, Stevenson,1971) consider that regional metamorphism tends to be an isochemical process, in rock subjected to greenschist and lower amphibolite facies conditions, unless there is clear evidence for the introduction of material by metasomatism. This would be manifest by the development of a more restricted mineralogy, varying according to the nature of the introduced material. Such addition of material would be expected along shear zones, where the transport of metasomatising fluids is enhanced, and at the contact of major intrusive bodies (Dostal, Strong & Jamieson, 1980).

Sample PJH78 (Table 4.4) was obtained from the Allt Luaidhe Semi-psammite Formation, within one metre of the contact of the Corrieyairack Granodiorite (NN 46909782). The sample has a hornfels texture, marked by the late growth of plagioclase porphyroblasts and, compared with the remainder of the metasediments, has higher concentrations of Na_2O, CaO, Ni, Cr, Zr, Sr and TiO_2 and lower K_2O (Table 4.4). Its unusual chemistry may be due to local metasomatism and contact metamorphism as a result of the intrusion of the granodiorite or possibly be the result of sampling an unrepresentative heavy mineral band within the sediment.

Sample PJH47 was obtained from the Coire nan Laogh Semi-pelite approximately 2 metres from the contact of the Corrieyairack Granodiorite (NN 44209740) and also has a hornfels texture, although not as pronounced as in Sample PJH78. This sample has slightly higher concentrations of Ba, Rb, K_2O and MgO and lower CaO than the remainder of the Coire nan Laogh Formation (Tables 4.4 & 4.7).

Samples up to 100 metres from the granodiorite contact, which is apparently steeply dipping (Chapter 7), continue to show the effects of thermal metamorphism, with the growth of fibrolite (Samples 7867 & 7869). These samples do not show late feldspar growths and do not have anomalous chemistries compared with the other metasediments. It would seem reasonable, therefore, to assume that extensive metasomatism, as a result of the intrusion of the Corrieyairack Granodiorite, was restricted to within two or three metres of the contact and involved addition of Na_2O, Sr and CaO in an inner zone and K_2O, Ba and Rb in an outer zone. Whether concentrations of Ni, Cr and TiO_2 also occur is unclear. However, large scale

TABLE 4.4: ANALYSES OF HORNFELSES.

Sample No.	78	47
SiO_2	52.47	63.40
TiO_2	1.61	.78
Al_2O_3	18.84	16.19
Fe_2O_3	4.88	.85
FeO	4.91	4.79
MnO	.15	.09
MgO	2.99	2.26
CaO	4.09	1.58
Na_2O	4.79	3.56
K_2O	2.80	4.72
P_2O_5	.30	.16
L.O.I.	1.19	1.31
Total	99.02	99.69
Rb	81	149
Sr	798	446
Ba	1401	1418
Ni	49	33
Y	20	33
Cr	105	49
Zr	684	265
Nb	22	21

77 Hornfels from Allt Luaidhe Semi-psammite (NN 46909782)

47 Hornfels from Coire nan Laogh Semi-pelite (NN 44209740)

late metasomatism is not apparent.

One explanation for the high K_2O concentrations in the Glenshirra Succession, is that the succession has been subjected to wholesale K_2O metasomatism. This would be manifest by the development of muscovite or alkali feldspar porphyroblasts if the metasomatism had taken place after the main deformational events. As already stated, metasomatism associated with the granodiorites is apparently restricted to a zone only a few metres wide and there is no systematic variation in K_2O with distance from the intrusion. As the two successions were juxtaposed early in their structural and metamorphic histories (Chapter 5), it seems unlikely that extensive K_2O metasomatism was restricted to one succession, unless it occurred prior to D1. This is unlikely, as there is little evidence of metamorphism preceding D1 (Chapter 6).

The good correlation within the two successions between K_2O and SiO_2 (Fig 4.3) and between K_2O, Ba and Rb (Figs 4.5 & 4.7) can also be cited as evidence for the restricted mobility of these elements during regional metamorphism, unless SiO_2 was also mobile. The scatter on the plot of Rb v K_2O (Fig 4.7) indicates some local mobility, although this may also be due to original sedimentary variation. Na_2O, CaO and Sr show a wide scatter and poor correlation with SiO_2 (Figs 4.2 & 4.3) and although this may represent original sedimentary variations, particularly with regard to plagioclase content, it may equally indicate some mobility of these elements during metamorphism.

In comparing the chemistry of the two successions and later the individual formations (Section 2d) it is therefore important to take into consideration the relative mobility of each element, particularly Rb, Sr, K_2O, Na_2O and CaO. Although it appears that there has been no large scale metasomatism, local redistribution of these elements may account for the considerable scatter and range of values. For this reason, comparison of mean values and element ratios for each succession is possibly more appropriate than the actual concentrations, when considering the nature of the original sediment.

By comparison with recent sediments it is possible to relate the geochemistry of the metasediments to the mineralogy of the original sediments. The source material of the original sediment falls into three main types (Nicholls, 1963) :

a. Material which has escaped chemical weathering; because it is resistant to chemical attack, for example: quartz, zircon and oxide phases due to rapid physical breakdown and deposition, for example: feldspars; or because the sediment was derived from a soft fine grained rock, eroded and transported without chemical attack, as with reworking of a pre-existing sediment.

b. Material which represents the solid product of chemical weathering of the source area, for example: clay minerals and chlorite.

c. Material reaching the depositional environment in solution and which is subsequently adsorbed onto clay minerals, particularly illite and montmorillonite, with the degree of adsorption controlled by the Eh and pH of the depositional environment.

The original sediment is therefore a combination of resistant detrital minerals and clay minerals, the detrital minerals giving a much clearer picture of the nature of the source area, than the chemically complex clay minerals.

Mafic minerals generally decay more rapidly than feldspars, and plagioclase more rapidly than alkali feldspars, depending on the conditions of weathering (Krauskopf, 1967). Na_2O, MgO and CaO, in particular, are readily lost into solution. Trace elements, in contrast, with the notable exceptions of Ba, Sr and Zr, are concentrated in the clay products of the mineral breakdown, by adsorption, and ion exchange.

The presence of the less resistant minerals in a sediment is therefore indicative of a rock which has undergone only a short weathering and transport history and is said to be 'chemically immature'. In contrast, a clay rich sediment is 'chemically mature' indicating either an extended weathering and transport history or derivation from a pre-existing sediment.

Na is present in the detrital sediments mainly in plagioclase, alkali feldspars and mica, and it has a lower concentration than K in clay minerals. Na_2O concentrations are slightly higher within the semi-pelites and psammites of the Corrieyairack Succession, compared to the Glenshirra Succession and may reflect either a higher proportion of feldspar to clay minerals or a higher proportion of plagioclase to alkali feldspar in the original pre-metamorphic phase assemblage of the succession.

One of the most pronounced differences between the two successions is the higher K_2O concentration in the Glenshirra Succession. K occurs principally in alkali feldspars and clay minerals, particularly illite and montmorillonite. The high concentration of K_2O would therefore indicate a higher proportion of alkali feldspar to plagioclase or a higher clay mineral content in rocks of the Glenshirra Succession. A higher alkali feldspar content would indicate rapid deposition of material, preventing breakdown of the relatively unstable alkali feldspar (Krauskopf, 1967) or that the material was derived from a different source to the plagioclase rich Corrieyairack Succession.

In contrast, if the high K_2O content represents a higher proportion of clay minerals, this would indicate that the Glenshirra Succession represented a more mature sediment, either as a result of a more extended transport and weathering history or derivation from a pre-existing sediment.

Comparison of the trace element concentrations with those of the major elements with which they exchange may help to establish whether the detrital material is dominated by feldspars or clay minerals, as Ni, Cr, Rb, Y, and Nb concentrations are generally enhanced in clays compared with their unweathered source material.

The high Rb concentration in the Glenshirra Succession is consistent with the high K_2O content. Rb^+ has a similar ionic radius to K^+ (1.41A cf. 1.33A) and therefore substitutes for K^+, usually in the later crystallizing K-minerals, particularly microcline, muscovite and biotite, (Wedepohl, 1969). It is concentrated relative to K_2O in shales, particularly marine shales, where Rb occurs principally in illite (K/Rb ratio in marine shales = 150-200 cf. 250-300 in fresh water or brackish shales). Due to the relative concentration of Rb in clays, the K/Rb ratio also decreases with reworking of the sediment and can be used as an index of 'maturity'.

In both successions the K/Rb ratio of the semi-pelites is consistent with a marine origin. It is higher within the semi-psammites and psammites of the Glenshirra Succession (Fig 4.7) which therefore suggests that a substantial proportion of the K_2O is present in alkali feldspar rather than in illite or montmorillonite.

Sr^{2+} (ionic radius 1.13A) also substitutes for K^+ in alkali feldspars, but due to its small ionic radius substitutes for K^+ in mica only to a limited extent. It can also substitute readily for Ca^{2+} in plagioclase and amphiboles as well as calcite, but as a result of changes in the plagioclase structure, the Sr content decreases with increasing anorthite content (Wedepohl, 1969).

Sr/Rb ratios decrease with increased sediment maturity (Cameron,1980) and this indicates that Sr is most probably held in plagioclase rather than in clay minerals (Calvert, 1976), although the Sr/Rb ratio may also be indicative of the proportion of feldspar to mica (Price and Wright, 1971).

The concentration of Sr and the Sr/Rb ratio are higher in rocks from the Corrieyairack Succession and indicate a predominance of feldspar over mica or of plagioclase over alkali feldspar. A higher proportion of plagioclase in the succession is consistent with the higher concentrations of CaO and Na_2O in these rocks.

Alternatively the CaO and Sr may have been present as carbonate in the original sediment. The high values for these elements in the Corrieyairack Succession suggesting a higher proportion of calcite. This model is supported by the increased number of calc-silicate bands, calcite bearing pods and modal calcite within rocks from the Corrieyairack Succession (Chapters 2 & 3).

Y^{3+} tends to follow Ca^{2+} but not all Ca-silicate minerals readily accept Y. Amongst the Ca-bearing minerals calcite, plagioclase and clino-pyroxenes are considered to be Y rejecting minerals (Lambert and Holland, 1974), whereas amphiboles, garnets, epidote, apatite, sphene, K-feldspar and micas are Y acceptor minerals. Y is also strongly adsorbed onto clay minerals.

Y concentrations in the two successions are very similar for each rock type, falling within the ranges quoted for recent sediments (shales 17-66ppm, greywackes 20-30ppm, sandstones 11-69ppm; Wedepohl,1969). This suggests that the CaO bearing phase in the Corrieyairack Succession is also a Y rejecting phase such as calcite or plagioclase. Although, as the Y content of calcite is < 10ppm and that of plagioclase is < 5ppm, giving CaO/Y ratios of c.40,000, the CaO/Y ratios of the two successions are too low for most of the Y to be contained in calcite or plagioclase (Lambert and Holland, 1974). Y is concentrated relative to CaO with reworking of sediments due to its adsorption onto clay minerats. It seems reasonable therefore that some Y is contained within clay minerals in both successions or within detrital epidote, sphene or apatite. The lower CaO/Y ratio of the Glenshirra Succession (mean values) suggests that the succession contains a higher proportion of clay minerals and may be more mature and more differentiated than the Corrieyairack Succession (Lambert and Holland, 1974). Sr/Y ratios can also be used as an index of sediment maturity; Sr indicating the presence of feldspars and Y the presence of clay minerals, although the ratio may also indicate the proportion of plagioclase (Sr) to alkali feldspar (Y) or mica (Y). Sr/Y is slightly lower in the psammites and semi-psammites of the Glenshirra Succession (mean values) than in those of the Corrieyairack Succession but slightly higher in the semi-pelites. Sr/Y in the psammitic lithologies again indicates either a higher proportion of clay minerals to feldspars or a higher proportion of mica or alkali feldspar to plagioclase or calcite in the Corrieyairack Succession. The lower values of CaO/Al_2O_3 in the Glenshirra Succession (mean values) (Fig 4. 7) also indicates the relative concentration of clay minerals or alkali feldspar or the lack of calcite in the Glenshirra Succession compared with the Corrieyairack Succession.

Ba also follows K^+ and to a lesser extent Ca^{2+} in feldspars and micas and also apatite and calcite. Early crystallizing K-feldspars have higher Ba concentrations than, for example microclines from pegmatites (Wedepohl, 1969) and this may be useful in distinguishing a less well differentiated source rock. Moore (1963) suggests that Ba is concentrated in arkosic sands and reflects the total feldspar content. The high Ba concentrations and the low Ba/Rb ratios in the Glenshirra Succession therefore indicates a higher proportion of feldspar to mica or K-feldspar to plagioclase (Price and Wright, 1971) than in the Corrieyairack Succession.

In the foregoing discussion two alternatives have been proposed as explanations of lower Sr/Y, CaO/Y and Sr/Rb ratios in the Glenshirra Succession :

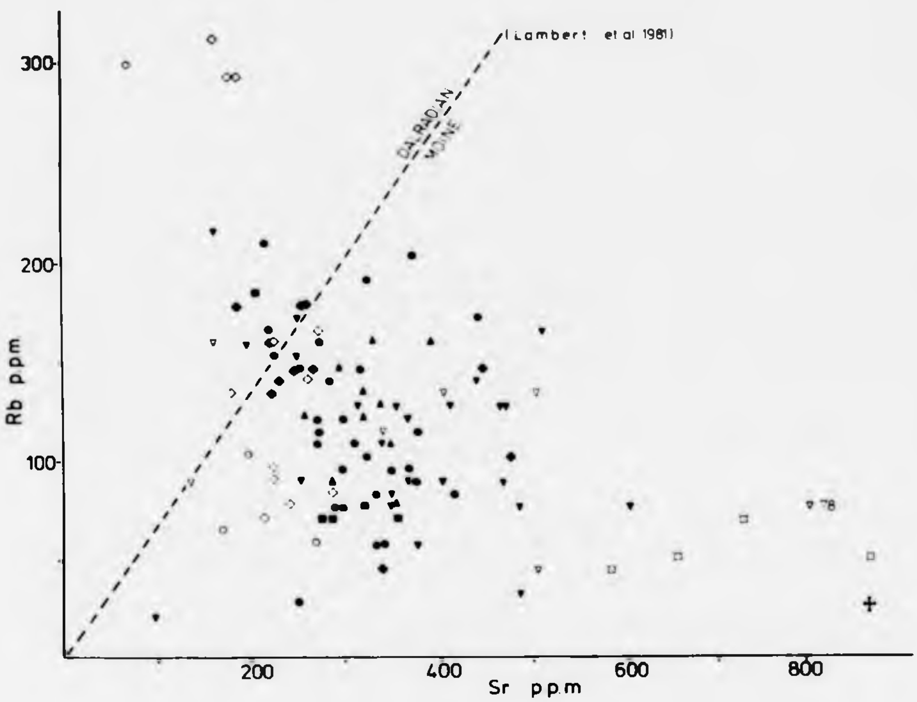
i. The Glenshirra Succession represents a more 'chemically mature' sediment, containing a higher proportion of clay minerals to feldspars than the Corrieyairack Succession, reflecting a different weathering and transport history or the reworking of a pre-existing sediment.

ii. The Glenshirra Succession contains a higher proportion of alkali feldspar or mica to plagioclase, than the Corrieyairack Succession, suggesting a different provenance for the two successions.

The higher Ba and higher K/Rb ratios of the Corrieyairack Succession suggest that the second alternative is more probable with Ba and K_2O present in alkali feldspar or mica and Rb representing the proportion of clay minerals (Hirst, 1962a & b). This is also suggested by the high K_2O/Na_2O ratio of the psammites, assuming that they represent original non-clay bearing sandstones (Blatt, Middleton & Murray, 1980).

Plots of log Na_2O/K_2O with log SiO_2/Al_2O_3 (Pettijohn, Potter & Siever, 1972) (Fig 4.8) suggest that the Glenshirra psammites and semi-psammites are closer to lithic arenites and arkoses in composition, whilst the Corrieyairack semi-psammites plot with the greywackes.

This distinction is also shown on a triangular plot of Na_2O:K_2O:$Fe_2O_{3(tot)}$+MgO (Blatt, Middleton & Murray, 1980) (Fig 4.9). Most of the samples from the Glenshirra Succession plot as 'taphrogeosynclinal' representing arkosic sandstones, derived from plutonic rocks of broadly granitic composition and relatively rich in K_2O and low in Fe_2O_3 and MgO. In contrast, most of the Corrieyairack samples plot as 'exogeosynclinal' and 'eugeosynclinal' lithic sandstones and greywackes respectively. Most of



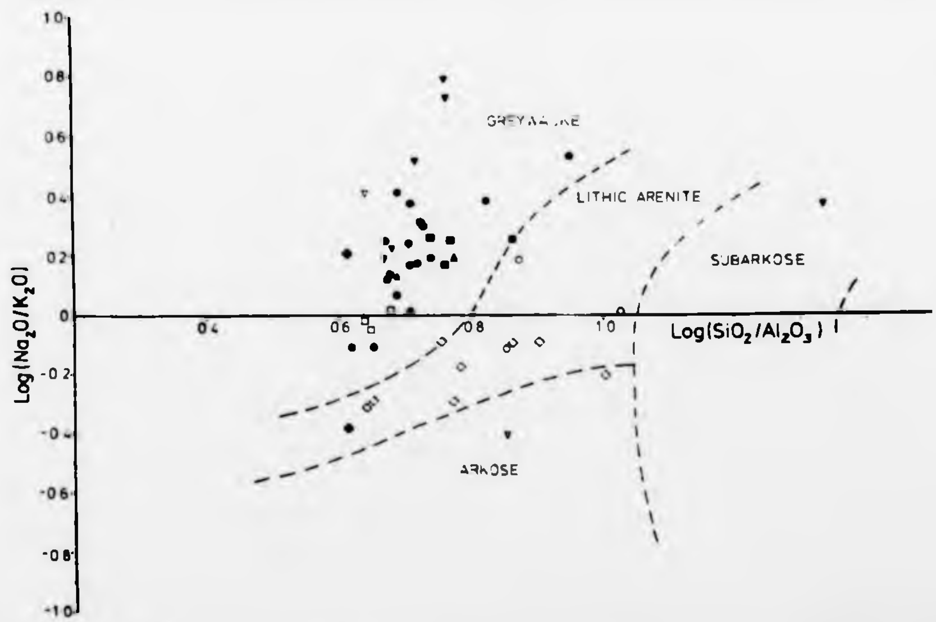


Figure 4.8: a) Rb v. Sr, b) Na_2O/K_2O v. SiO_2/Al_2O_3 for semi-psammites, after Pettijohn, et al.(1972).

Figure 4.9 : A. Fe_2O_3 tot. + MgO - Na_2O - K_2O triangular diagram fields from Blatt, et al. (1980).

Figure 4.9 : B. A.F.M. Diagram showing positions of means of main sandstone types

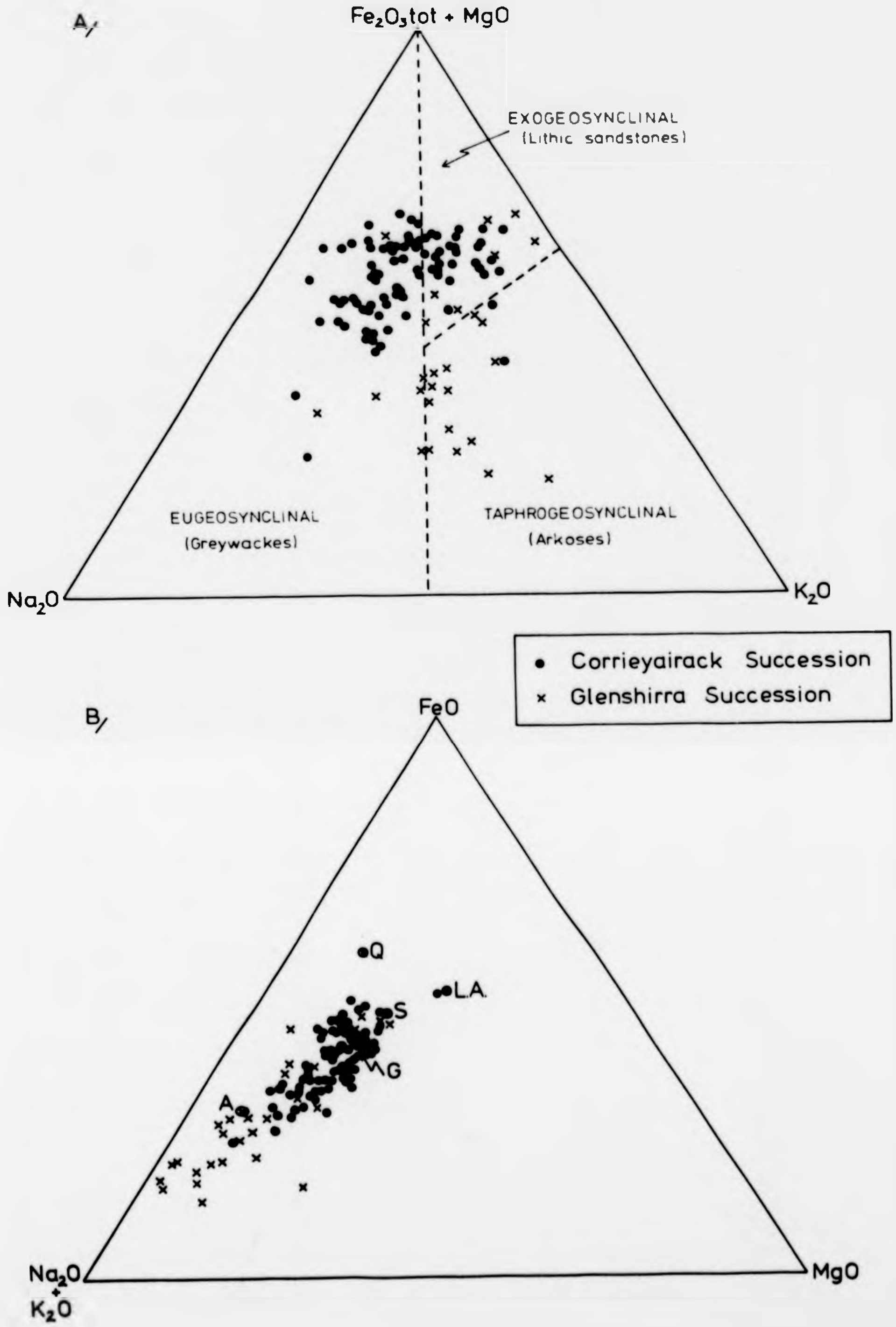
A: Arkose (Pettijohn, 1963)

G: Greywacke (Pettijohn, 1963)

L.A: Lithic arenite (Pettijohn, 1963)

Q: Quartzite (Pettijohn, 1963)

S: Shale (Van de Kamp, et al., 1976)


A/
Fe_2O_3tot + MgO
EXOGEOSYNCLINAL
(Lithic sandstones)
EUGEOSYNCLINAL
(Greywackes)
TAPHROGEOSYNCLINAL
(Arkoses)
Na_2O
K_2O
• Corrieyairack Succession
× Glenshirra Succession
B/
FeO
Q
L.A.
S
G
A
Na_2O + K_2O
MgO

the differences between arkoses and greywackes reflect a source control and also the action or ground water on the arkosic sandstones resulting in the loss of MgO in solution and the retention of iron as Fe_2O_3 rather than FeO. The high Na_2O/K_2O ratio in greywackes may be the result of albitization of plagioclase during diagenesis, the presence of albite rich rock fragments and the characteristically rapid deposition, preserving Na_2O in plagioclase rather than replacing it by K_2O during the formation of the clay minerals (Blatt, et al., op.cit.).

However, the Na_2O/K_2O ratio chiefly depends upon the composition of the detrital feldspar and does not distinguish greywackes from muddy sandstones. The range in composition of the samples in each succession therefore may reflect varying proportions of clay minerals in sandstones which are subarkosic rather than the presence of greywackes (Lambert, Winchester and Holland, 1981).

In a plot of Niggli al-alk with K_2O (Senior and Leake, 1978) (Fig 4.10 al-alk is taken to be a measure of the Al_2O_3 which was contained in clays and mica in the original sediment, therefore plots against al-alk should show whether the concentration of particular elements is controlled chiefly by the clay minerals and mica content of the original sediment. The Glenshirra rocks tend to have higher values of K_2O than the Corrieyairack samples for the same proportion of clay and mica. They therefore contained before metamorphism either a higher proportion of K_2O bearing clay (for example, illite), a higher proportion of K_2O bearing mica, or the K_2O content is not controlled by the clay and mica but by alkali feldspar. In an A.F.M. diagram (Fig 4. 9) the samples plot on a calc-alkaline type trend (Robinson and Leake, 1975) indicating an increase of $Na_2O + K_2O$ in relation to a fairly constant FeO/MgO ratio. FeO and MgO are chiefly controlled by the clay minerals and mica, therefore the trend indicates an increase in alkali feldspar and sodic plagioclase. The Glenshirra rocks

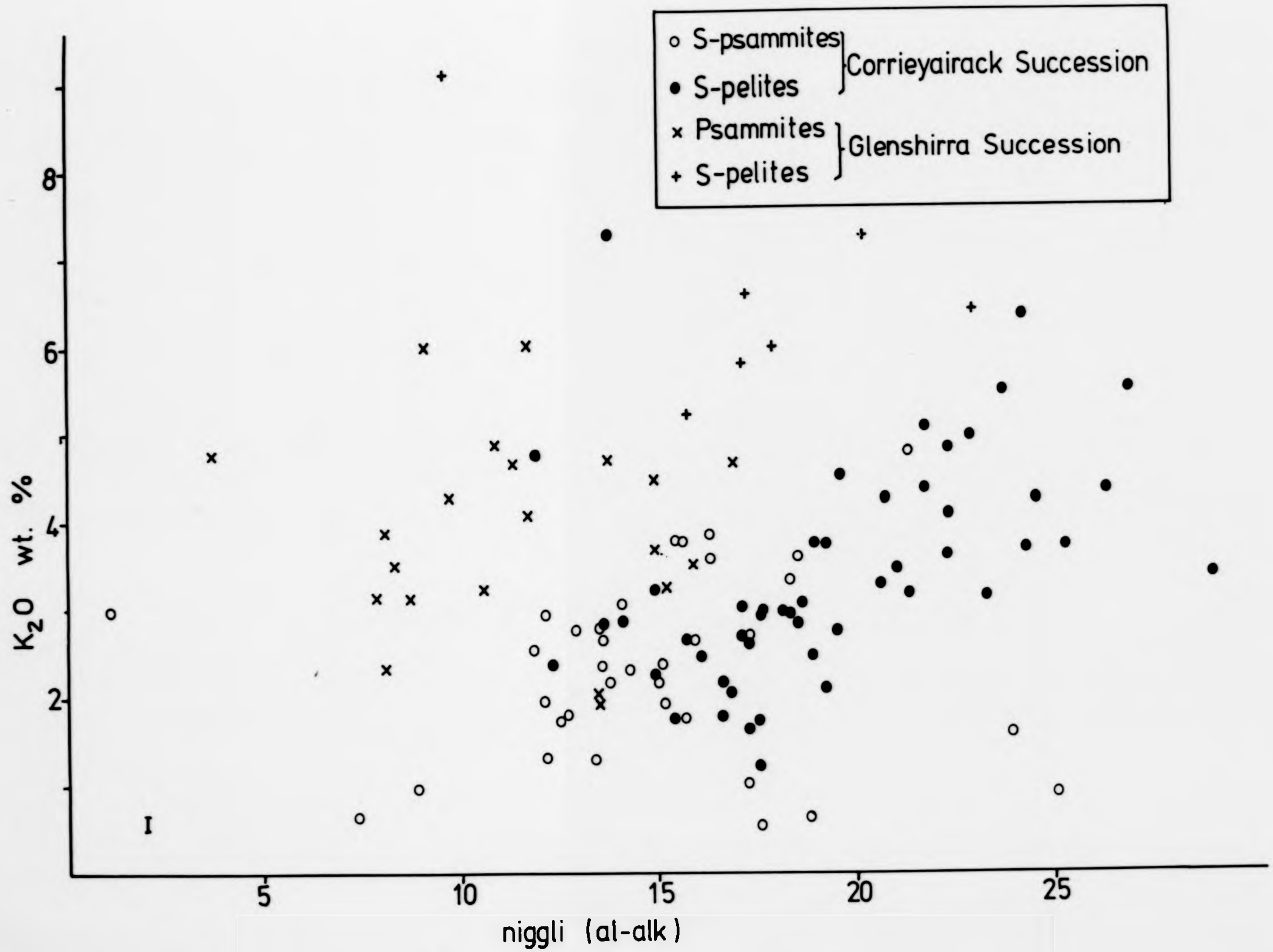


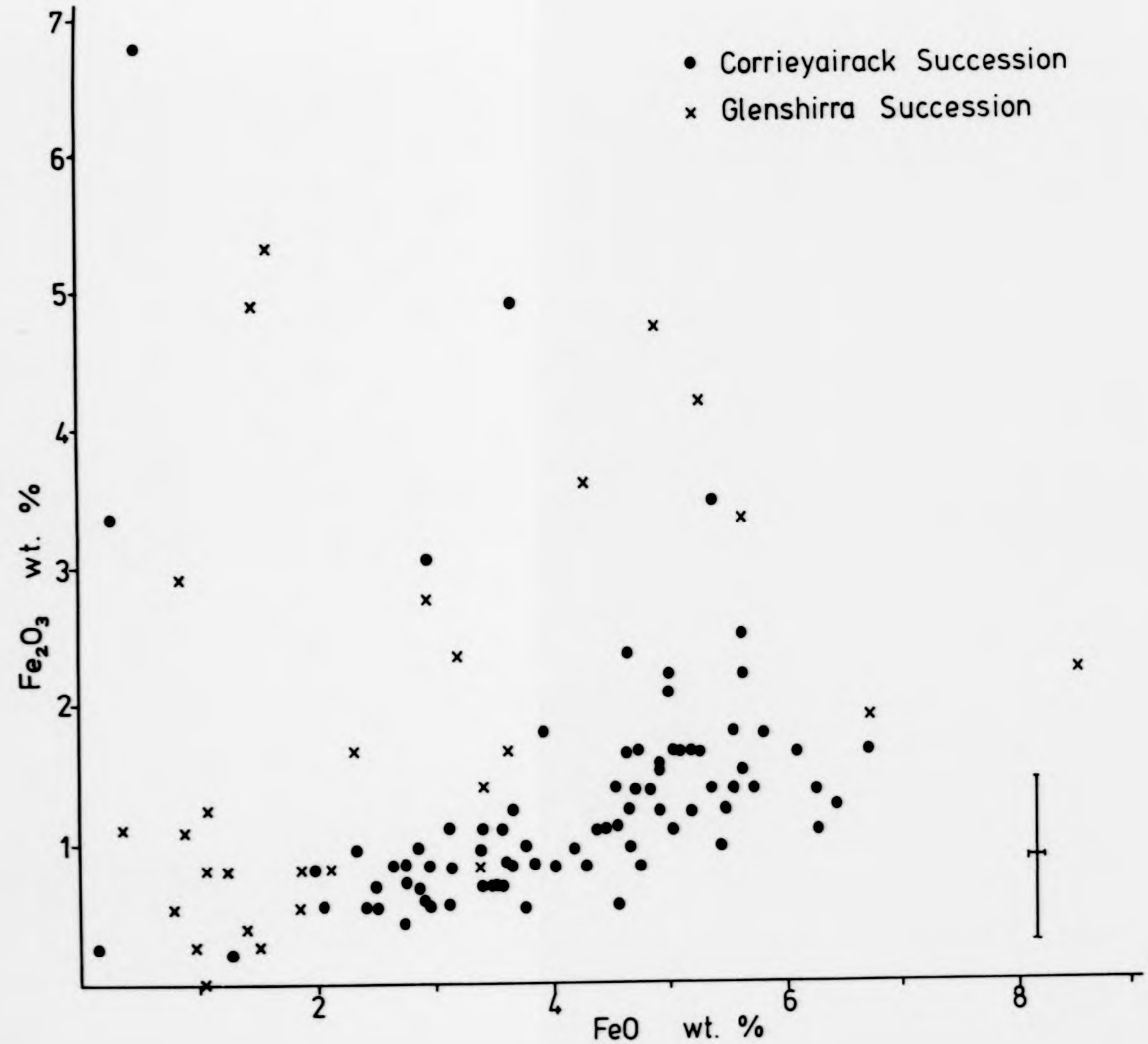
Figure 4.10: K_2O v. Niggli (al-alk), after Senior and Leake (1978).

plot in the higher $Na_2O + K_2O$ range indicating a higher proportion of feldspar, particularly in the more psammitic rocks. Comparison with averages of the major sandstones (Pettijohn, 1963) shows that this is not simply an effect of increasing SiO_2 and that again the Glenshirra rocks are arkosic in composition and the Corrieyairack rocks are more like greywackes.

Nickel and chromium occur predominantly within the minor detrital phases such as garnet, magnetite and rutile, replacing Al^{3+}, Fe^{3+} or Mg^{2+}, although both elements are easily removed by weathering and can be concentrated in the clay fraction of the sediment. The concentration of both elements in the sediment is controlled mainly by the ratio of mafic to granitic rocks in the source area (Wedepohl, 1969). Therefore the lower values for these elements in the Corrieyairack Succession hints that it is derived from a lower proportion of basic source rock than the Glenshirra Succession.

Both successions contain similar proportions of total Fe (higher mean values in Glenshirra Succession largely due to low SiO_2 in mean). However, the mean values for the ratio of Fe_2O_3/FeO is higher in the Glenshirra Succession than in the Corrieyairack Succession indicating a more oxidised environment consistent with their arkosic nature. This is particularly true for the psammites and semi-psammites although the Glenshirra Succession shows a wide scatter of values (Fig 4.11). The difference in oxidation state of the two successions is discussed in more detail in Section 6.

In summary : The variations in chemistry between the two successions indicates that the Glenshirra Succession represents a group of sediments that is less 'mature' than the Corrieyairack Succession, with a higher proportion of alkali feldspar to plagioclase and feldspar to clay minerals and representing a sediment of broadly arkosic composition. The



Corrieyairack Succession
Glenshirra Succession
Fe2O3 wt. %
FeO wt. %

Figure 4.11:

Corrieyairack Succession, in contrast, represents original sediment more like greywackes in composition. These differences may be due to derivation of the Glenshirra Succession from a more alkali feldspar rich or granitic source, although the Ni and Cr concentrations indicate some mafic component in the source area, perhaps indicating a mixed provenance or that the detrital material was subjected to a less intensive transport and weathering history.

d. Variation between Formations.

i. Glenshirra Succession.

As stated in the introduction, the Glenshirra Succession is represented by a relatively small number of samples (28). Comparisons between the formations must therefore be treated with caution as the samples may not be representative of each formation as a whole, particularly where the standard deviations are large.

The Gairbeinn Pebbly Semi-psammite Formation has a markedly different chemistry from the rest of the succession and from the Corrieyairack Succession. Although no large clastic fragments were included in the samples which were chosen to represent the matrix of the pebbly formation, the internal variation and unusual overall chemistry may partly result from the inclusion of smaller detrital rock fragments within the analysed fraction.

Compared with the rest of the succession, the formation has higher Ba, CaO, TiO_2, Fe_2O_3 concentrations, markedly higher Sr concentration, and lower concentrations of Y, Rb, Cr, Ni, Nb and MgO (Table 4.5) resulting in very much higher Sr/Y and Sr/Rb ratios. These differences all point

TABLE 4.5

	A		B		C		D		E	
SiO_2	65.08	4.85	66.92	8.08	66.72	1.55	80.25	3.62	76.76	3.57
TiO_2	1.09	.80	.74	.09	.57	.20	.33	.11	.33	.11
Al_2O_3	15.93	2.15	15.46	3.26	14.99	.22	9.75	1.62	11.00	1.65
Fe_2O_3	2.27	1.74	1.69	.60	1.17	.41	.78	.43	.84	.78
FeO	2.03	1.05	1.74	.03	3.42	.01	1.05	.20	1.14	.56
MnO	.08	.02	.08	.01	.09	.00	.07	.05	.05	.01
MgO	1.28	.57	1.29	1.24	1.49	.26	.17	.13	1.01	.99
CaO	2.85	.35	1.39	.86	1.27	.22	1.01	.62	1.06	.22
Na_2O	3.61	.53	3.69	1.43	2.65	.41	2.81	.37	2.80	.60
K_2O	3.80	.48	4.41	1.67	5.32	.94	2.72	1.02	3.82	.72
P_2O_5	.12	.07	.18	.13	.13	.07	.05	.02	.07	.03
Rb	58	27	98	37	166	6	78	22	102	28
Sr	709	333	343	233	246	34	215	53	234	34
Ba	1802	874	1268	611	1068	76	802	144	886	126
Ni	18	5	19	11	27	13	59	39	14	3
Y	9	4	19	9	21	13	13	7	13	6
Cr	34	10	29	25	39	10	20	4	18	5
Zr	259	154	319	84	135	64	161	94	191	119
Nb	14	12	26	11	20	1	29	5	28	8

A Mean of semi-psammites from Gairbeinn Pebbly Semi-psammite (5 analyses)

B Mean of semi-psammites from Allt Luaidhe Semi-psammite (4 analyses)

C Mean of semi-psammites from Creag Mhor Psammite (2 analyses)

D Mean of psammites from Carn Dearg Psammite (3 analyses)

E Mean of psammites from Creag Mhor Psammite (7 analyses)

COMPARISON OF SEMI-PSAMMITES AND PSAMMITES FROM THE GLENSHIRRA SUCCESSION.

to the 'chemical immaturity' of the original sediment (Section 2e), with the high values of Ba and Sr indicating a high feldspar content, and low concentrations of Y, Rb, Cr, Ni and Nb, pointing to a low clay content. The low concentration of Cr, Ni and Nb also indicate a low content of mafic minerals suggesting that the sediment was derived from a 'well differentiated' source rock. The higher K/Rb ratios and low Ca/Sr ratios are also more compatible with a fresh water origin (Campbell & Lerbekmo,1963, Wedepohl,1969).

The high concentrations of TiO_2, Fe_2O_3 and possibly CaO in some samples, may be associated with the presence of 'heavy' detrital minerals such as ilmenite, rutile and epidote. P_2O_5 concentrations are similar to those of the rest of the succession, and apatite was therefore not particularly concentrated in the sediment.

The 'immaturity' of the Gairbeinn Pebbly Semi-psammite means that it is more likely to retain many of the chemical characteristics of the rocks from which it was derived than the other formations. Comparisons with average analyses of possible source rocks, including the Lewisian or 'older' Moine rocks northwest of the Great Glen Fault (Tables 4.11 & 4.12) reveal several important differences.

Compared with the Lewisian (Table 4.11), the Gairbeinn Pebbly Semi-psammite has a similarly high Sr/Y ratio but has higher concentrations of TiO_2, K_2O and Ba, but lower MgO, CaO, Na_2O, Ni and Cr. It also has lower Ca/Y and Ca/Sr and higher Zr/P_2O_5 ratios. Although many of these differences could be explained by the effects of chemical weathering, for example, the removal of sodic feldspars and the deposition of K_2O rich clay minerals, the differences are large enough to suggest that the Lewisian basement was not the source rock for this formation. Comparison with the Morar Basal Pelite, which directly overlies the Lewisian and has a chemistry which supports a model for its derivation from the Lewisian (Winchester, Lambert & Holland, 1981) and is intermediate between the Lewisian and the overlying Morar Division, also suggests that the Gairbeinn Pebbly Semi-psammite may not have been derived from the Lewisian.

The Gairbeinn Pebbly Semi-psammite has higher concentrations of Sr, Ba, Nb, and TiO_2 and lower concentrations of MgO, P_2O_5, Rb, Y, Ni, Cr and Zr than the Morar Basal Pelite, resulting in an even higher Sr/Y ratio than that which makes the Morar Basal Pelite so distinctive (Winchester, et al.,1981). The Gairbeinn Pebbly Semi-psammite is therefore no more 'mature' than the Morar Basal Pelite and hence its other chemical differences hint that it may be from a basement source other than the Lewisian.

Plots of TiO_2 v SiO_2 (Tarney, 1977) and log Zr/TiO_2 v Ni (Winchester, Park & Holland, 1980) designed to distinguish between metasedimentary and meta-igneous rocks, suggest that there is a substantial proportion of igneous material in the source area of both the successions in the Corrieyairack area, as the samples generally plot across the sedimentary/igneous dividing line (Figs 4.4 & 4.12). The presence of microcline clasts in the pebbly formation and abundant quartz pebbles suggests that the source was generally of granitic composition, but it is not possible to establish more precisely the nature of the source rock.

The average analyses for each formation (Tables 4.5 & 4.6) in the Glenshirra Succession, particularly the semi-psammites, as the numbers of the analyses of this rock type are more comparable, show a steady drop in the concentration of TiO_2, CaO, Na_2O, Sr and Ba and an increase in K_2O and Rb down the succession. The Creag Mhor Formation is also characterized by a lower $Fe_2O_3/Fe_2O_{3(total)}$ ratio indicating a less oxidised environment.

The ratios K/Rb, Sr/Rb, Ba/Rb, Ca/Y and Nb/Y also decrease down the

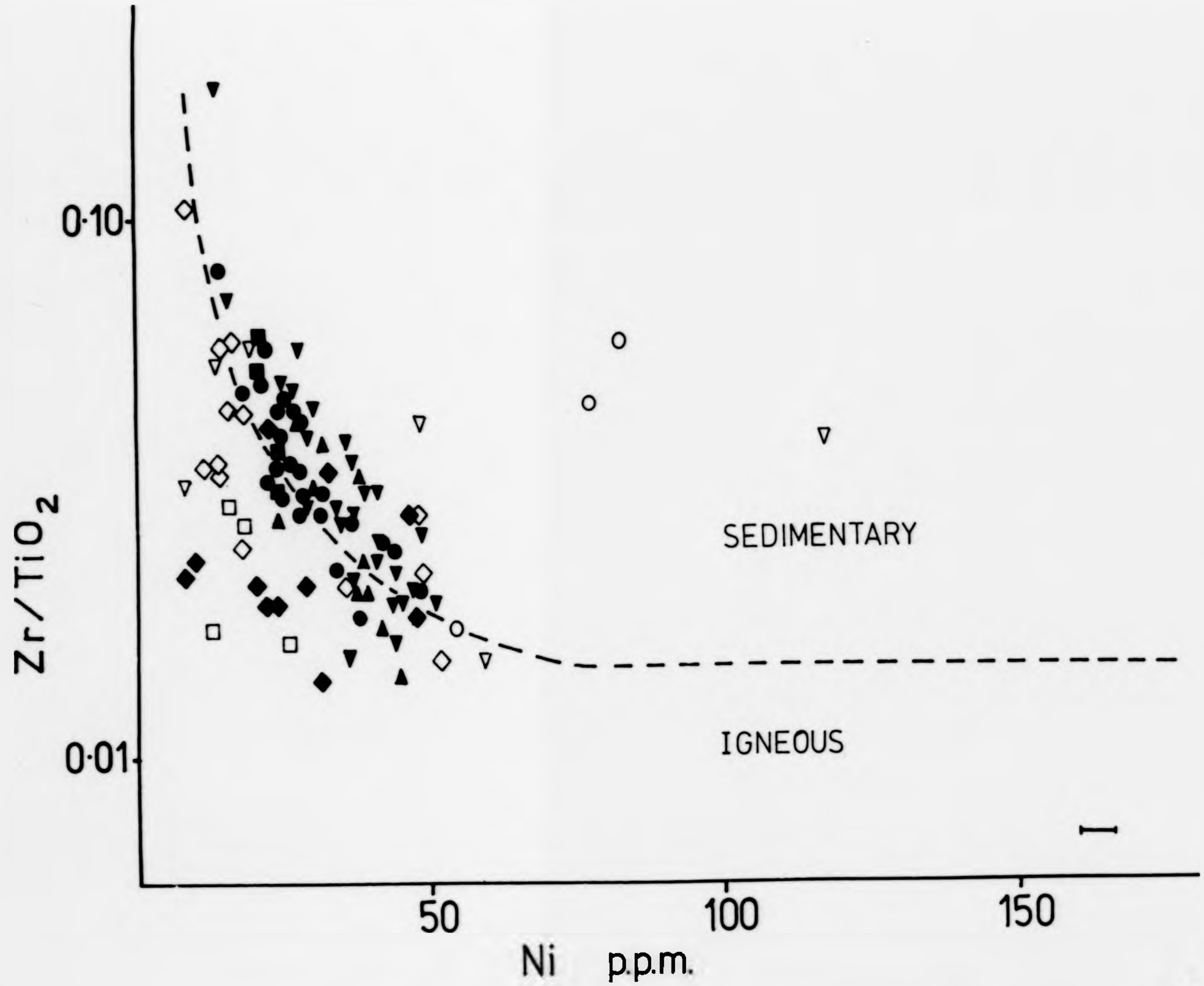


Figure 4.12: Zr/TiO$_2$ v. Ni after Winchester, et al. (1980), (Key as for figure 4.2).

TABLE 4.6

	A		B	C	
SiO_2	56.00	4.24	54.96	53.95	3.50
TiO_2	1.05	.01	1.07	1.09	.24
Al_2O_3	19.42	1.29	18.63	18.82	1.58
Fe_2O_3	4.79	.76	3.45	2.73	.87
FeO	3.47	2.63	5.65	6.52	2.13
MnO	.15	.08	.17	.19	.04
MgO	2.81	1.73	3.13	3.51	.80
CaO	1.59	.57	.54	1.28	.21
Na_2O	2.03	1.94	.56	1.94	.21
K_2O	5.77	.82	7.22	7.14	1.72
P_2O_5	.33	.06	.28	.23	.04
Rb	153	18	307	304	8
Sr	283	173	75	176	16
Ba	1269	15	1265	1099	143
Ni	88	41	55	49	1
Y	33	0	30	49	7
Cr	83	37	81	82	12
Zr	280	166	183	253	119
Nb	15	3	27	23	2

A Mean of semi-pelites from Allt Luaidhe Semi-psammite (2 analyses)

B Semi-pelite from Carn Dearg Psammite (Sample no. PJH 263)

C Mean of semi-pelites from Creag Mhor Psammite (3 analyses)

COMPARISON OF SEMI-PELITES FROM THE GLENSHIRRA SUCCESSION.

succession whilst K/Ba increases. If Rb is an indicator of the relative proportion of clay minerals present (Calvert, 1976) and Ba correspondingly an indication of the total feldspar content (Moore, 1963), then these ratios indicate a decrease in the clay mineral content up the succession, or a decrease in the 'maturity' of the sediment.

The increase in CaO, Na_2O and Sr, and decrease in K_2O and Rb up the succession may indicate an increase in the proportion of plagioclase in the sediment, possibly due to a gradual change of provenance. This may also be indicated by the increase in Zr/P_2O_5 in which Zr represents detrital zircons and P_2O_5 detrital apatite.

Looking at the succession as a whole, the chemistry is consistent with the following regime: deposition of the Creag Mhor Psammite possibly in a shallow marine environment, suggested by the field characteristics of the sediments (Chapter 2), with a rapidly uplifted basement source area and emergent depositional environment producing an increasingly immature sediment, culminating in the deposition of the Gairbeinn Pebbly Semi-psammite, possibly in an alluvial fan or braided stream environment (Chapter 5).

ii. Corrieyairack Succession.

Semi-pelitic Rocks.

Comparison of analyses from the Tarff Gorge and from the main outcrop of the Monadhliath Semi-pelite (Table 4.7), supports the proposal (Chapter 2) that these two semi-pelites are part of the same formation. The average analyses of the semi-pelites are very similar, and the two groups of samples show considerable overlap on most variation diagrams. The Tarff Gorge semi-pelites have slightly higher concentrations of MgO, apparent on a variation diagram of MgO v Al_2O_3 (Fig 4.13) and also MgO v SiO_2 (Fig 4.4). In view of the lack of calc-silicate bands in the Tarff Gorge

TABLE 4.7

	A		B		C		D	
SiO_2	60.63	3.26	60.76	2.99	59.25	4.51	59.59	4.09
TiO_2	.87	.12	.87	.09	.88	.13	.91	.14
Al_2O_3	17.41	1.88	16.99	1.69	17.99	1.57	18.46	1.73
Fe_2O_3	1.54	.75	1.55	.24	1.30	.19	2.84	1.76
FeO	5.01	.91	5.39	.82	4.82	1.13	3.84	1.89
MnO	.15	.05	.12	03	.12	.03	.13	.10
MgO	2.41	.50	2.86	.44	2.70	.42	2.20	.55
CaO	2.56	.86	2.32	.58	1.91	.76	1.89	.51
Na_2O	3.49	1.05	3.05	.44	2.46	.52	2.68	.91
K_2O	2.91	1.15	3.02	.51	4.71	1.67	3.83	.65
P_2O_5	.27	.12	.28	.03	.33	.18	.29	.08
Rb	132	37	131	26	167	39	157	18
Sr	357	103	325	42	275	65	262	78
Ba	768	305	797	110	1245	241	1019	262
Ni	38	7	38	5	39	7	23	9
Y	37	11	35	6	36	12	34	5
Cr	62	12	60	9	59	9	57	11
Zr	241	86	219	69	219	54	197	40
Nb	25	4	23	5	22	8	29	5

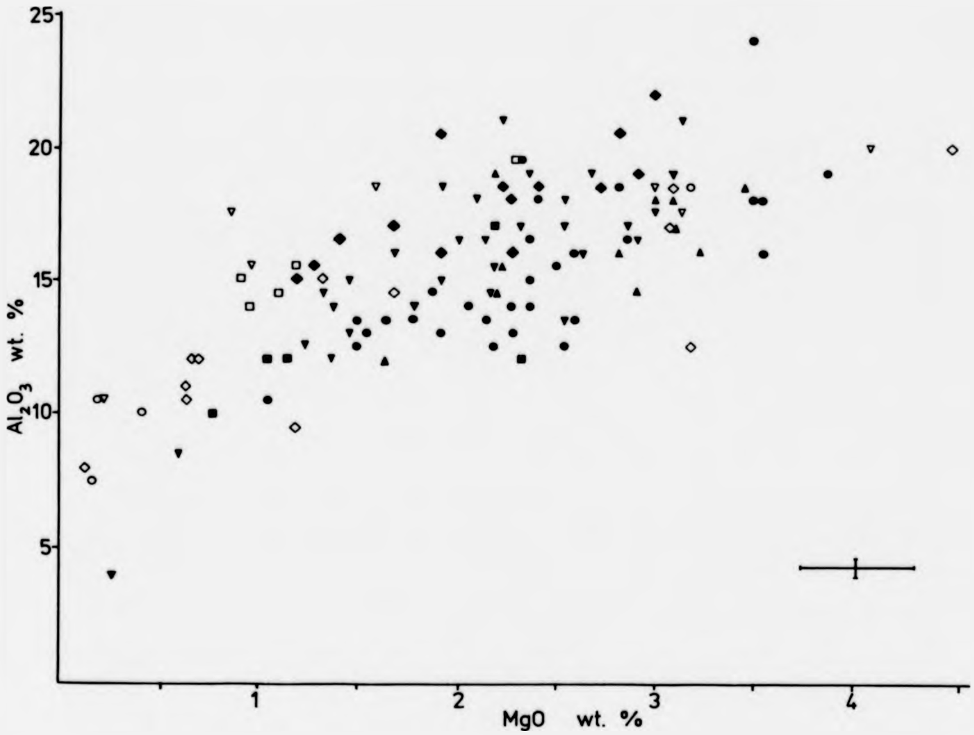
A Mean of semi-pelites from Monadhliath Semi-pelite (23 analyses)

B Mean of semi-pelites from the Tarff Gorge (9 analyses)

C Mean of semi-pelites from Knockchoilum Semi-psammite (6 analyses)

D Mean of semi-pelites from Coire nan Laogh Semi-pelite (10 analyses)

COMPARISON OF SEMI-PELITES FROM THE CORRIEYAIRACK SUCCESSION.



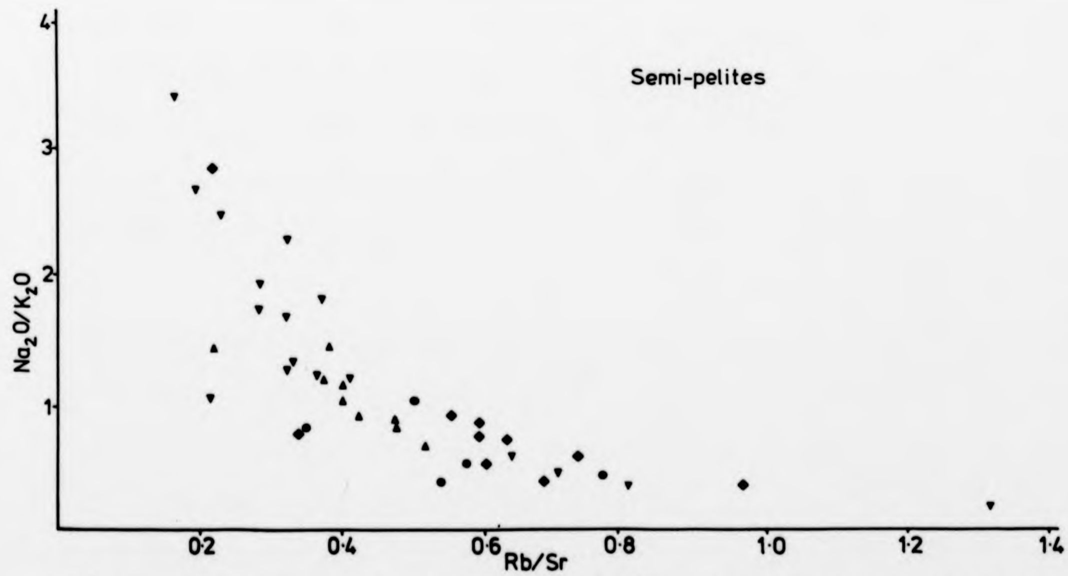


Figure 4.13: a) Al_2O_3 v. MgO, b) Na_2O/K_2O v. Rb/Sr for semi-pelites from the Corrieyairack Succession (Key as for figure 4.2).

section, possibly due to slight variations in the environment of deposition of the original sediment, small geochemical differences are to be expected, and the variation in MgO/Al_2O_3 may simply indicate a higher concentration of montmorillonite in the clay fraction of the sediment (Calvert, 1976).

Comparison of the two major semi-pelitic formations: the Monadhliath Semi-pelite and the Coire nan Laogh Semi-pelite by contrast reveal several differences, supporting the field interpretation that these formations occur at different stratigraphic levels, rather than one being an infold of the other; a possibility suggested by Anderson (1956).

The Coire nan Laogh Semi-pelite has slightly lower concentrations of CaO, Sr, Na_2O, Zr and Ni, and higher concentrations of Rb, Ba and K_2O. The value for al-alk (Fig 4.10) is also higher, and a higher proportion of clay minerals compared with feldspar suggested by these values would explain the lower Na_2O, CaO and Sr, indicating a relative lack of plagioclase.

The Coire nan Laogh Semi-pelite has a very similar composition to the semi-pelitic fraction from the Knockchoilum Semi-psammite suggesting that both formations represent slightly more 'mature' sediments compared with the Monadhliath Semi-pelite, either due to an increased destance from the sediment source or erosion of a more clay rich pre-existing sediment.

It has been proposed that the migmatitic Semi-pelite at the base of the Corrieyairack Succession represented the basal part of the Coire nan Laogh Semi-pelite affected by movement on the Gairbeinn Slide (Chapter 7). This produced insitu recrystallization without extensive metasomatism by percolating fluids.

This model is supported by comparison of the 'migmatitic' and 'non-migmatitic' semi-pelites. The average compositions (Table 4.8) show very few differences, these being only the oxidation state of iron, and concentrations of Ba and Nb. The migmatitic semi-pelite is slightly more oxidised than the non-migmatitic. This may be due to the difficulty in obtaining fresh, unweathered samples of the coarser grained material. The loss of Ba, increase in Nb and possibly the variation in oxidation state may be attributed to the local movement of hydrothermal fluids during recrystallization (Chapter 3).

Semi-psammitic Rocks.

The Carn Leac Semi-sammite and Knockchoilum Semi-psammite can not be distinguished on the basis of their geochemistry, as their average analyses (Table 4.9) are almost identical despite the discrepancy in sample size, and the two formations plot in the same fields on most variation diagrams, although, the Carn Leac samples do have lower MgO and P_2O_5 concentrations and a higher Zr/P_2O_5 ratio. The geochemistry of the two formations cannot therefore be used as a basis for stratigraphic correlation.

The two samples from the Tarff Gorge section have higher concentrations of MgO, Rb, and Ba, and lower concentrations of Sr and Zr than the samples from the Monadhliath Semi-pelite, but considering the small sample size and the standard deviations of the average analyses, these differences are probably not reliable.

The Knockchoilum Semi-psammite has higher average concentrations of MgO, K_2O, Ba, Rb and Cr than the Monadhliath or Coire nan Laogh Formations, but on most variation diagrams all the formations of the Corrieyairack Succession show considerable overlap and cannot be distinguished. The only exceptions are a plot of Al_2O_3 v MgO (Fig 4.13) and Na_2O/K_2O v Rb/Sr (Fig 4.13). Psammites from the Monadhliath Semi-pelite have a higher Al_2O_3/MgO ratio than those from the Knockchoilum Semi-psammite, possibly

TABLE 4.8

	A		B	
SiO_2	59.77	5.25	59.40	3.15
TiO_2	.88	.18	.94	.10
Al_2O_3	18.26	2.16	18.67	1.40
Fe_2O_3	2.70	1.57	2.99	2.13
FeO	3.86	2.12	3.82	1.89
MnO	.16	.14	.10	.02
MgO	2.31	.65	2.09	.48
CaO	1.99	.70	1.78	.28
Na_2O	2.75	1.29	2.62	.42
K_2O	4.03	.84	3.63	.40
P_2O_5	.28	.10	.29	.05
Rb	165	16	152	19
Sr	287	139	248	18
Ba	1278	216	865	130
Ni	27	7	19	9
Y	31	4	37	5
Cr	55	14	59	9
Zr	198	64	196	29
Nb	23	3	32	3

A Mean of non- migmatitic semi-pelites from Coire nan Laogh Semi-pelite (5 analyses)

B Mean of migmatitic semi-pelites from Coire nan Laogh Semi-pelite (5 analyses)

COMPARISON OF 'MIGMATITIC' AND 'NON-MIGMATITIC' SEMI-PELITES FROM THE COIRE NAN LAOGH SEMI-PELITE.

TABLE 4.9

	A		B		C		D		E	
SiO_2	70.45	5.56	70.01	1.78	70.21	4.72	66.84	4.06	65.31	2.67
TiO_2	.64	.14	.55	.11	.59	.12	.67	.15	.64	.06
Al_2O_3	12.95	2.47	13.47	.89	14.01	1.66	14.17	1.79	17.08	1.93
Fe_2O_3	1.05	.26	.78	.18	.81	.10	1.03	.50	.97	.13
FeO	2.87	.99	2.91	.25	3.25	.45	3.72	1.06	3.74	.45
MnO	.09	.03	.12	.06	.09	.02	.11	.04	.25	.02
MgO	1.47	.69	1.40	.19	1.92	.28	2.16	.64	1.58	.36
CaO	2.03	1.22	2.65	.85	1.91	.33	2.51	1.70	4.05	1.13
Na_2O	3.01	.65	3.87	.43	3.43	.06	3.37	.50	3.48	1.39
K_2O	2.51	1.29	1.75	1.04	2.42	.24	2.63	.84	1.43	.45
P_2O_5	.15	.03	.14	.06	.17	.06	.21	.09	.35	.14
Rb	98	50	71	24	102	14	106	30	76	42
Sr	292	56	439	107	319	47	327	51	410	98
Ba	655	293	516	325	704	219	677	216	350	280
Ni	26	8	25	5	27	4	28	6	36	12
Y	24	7	22	5	22	6	29	6	25	3
Cr	36	11	34	3	34	6	42	7	38	7
Zr	263	129	270	129	113	157	250	107	219	31
Nb	28	4	24	7	21	1	24	5	29	9

A Mean of semi-psammites from Carn Leac Semi-psammite (5 analyses)

B Mean of semi-psammites from Monadhliath Semi-pelite (6 analyses)

C Mean of semi-psammites from the Tarff Gorge (2 analyses)

D Mean of semi-psammites from Knockchoilum Semi-psammite (21 analyses)

E Mean of semi-psammites from Coire nan Laogh Semi-pelite (3 analyses)

COMPARISON OF SEMI-PSAMMITES FROM THE CORRIEYAIRACK SUCCESSION.

indicating a lower proportion of montmorillonite in the clay fraction (Calvert, 1976). The Monadhliath Semi-pelite also has higher Na_2O/K_2O ratios than the Coire nan Laogh Semi-pelite for the same Rb/Sr ratio and the semi-pelites from the Tarff Gorge and the Knockchoilum Formation are transitional between the two, indicating a decrease in the maturity of the sediment up through the succession, with a reduction in the proportion of clay minerals and increase in plagioclase feldspar.

e. Comparison with Other Metasediments from the Highlands.

Lambert, Winchester and Holland (1981) suggest that the chemically mature nature of the semi-pelites from the lower part of the Appin Group of the Dalradian, produces characteristic trace element ratios: $CaO/Y < 310$, $P_2O_5/Y < 55$, $K/Rb < 240$ and $Rb/Sr > 0.65$ and that these ratios can be used to distinguish between Dalradian and Moine semi-pelites.

Anderson (1956) correlated the Monadhliath Schist of the Corrieyairack area, with the Leven Schists of Glen Roy. It has already been shown that the two semi-pelites occur at different stratigraphic levels (Chapter 2) (Haselock and Winchester, 1981) separated by the Carn Leac Semi-psammite, and the field evidence is supported by differences in the geochemistry of the two semi-pelites (Tables 4.7 & 4.10).

Compared to the Leven Schists the Monadhliath Semi-pelite from the Corrieyairack area has higher concentrations of MnO, CaO, Na_2O and Sr, and lower values of Al_2O_3, K_2O, Rb, Y and Zr. On the Dalradian/Moine discrimination diagrams of Lambert, et al. (1981) the Monadhliath Semi-pelite plots almost entirely within the Moine field (Figs 4.14 & 4.16). Similarly the remainder of the Corrieyairack Succession plots consistently within the Moine field.

TABLE 4.10

	A		B		C		D	E
SiO_2	94.57	2.19	82.23	4.64	72.03	2.54	63.14	60.30
TiO_2	.10	.07	.27	.17	.70	.26	.78	.81
Al_2O_3	2.96	1.46	9.92	2.47	12.77	3.14	20.09	23.02
Fe_2O_3	.29	.14	1.33	.63	3.14	.87	6.02	6.01
MnO	.05	.01	.02	.01	.05	.02	.08	.08
MgO	.09	.06	.32	.22	1.81	3.08	2.25	1.87
CaO	.06	.04	.73	.74	2.20	1.50	1.17	.83
Na_2O	.60	.38	2.54	.87	3.11	1.28	2.24	1.92
K_2O	1.13	.80	2.63	.65	3.26	.97	4.07	4.78
P_2O_5	.01	.01	.01	.02	.06	.05	.14	.12
Rb	35	22	64	17	84	27	207	206
Sr	27	21	143	72	179	70	165	146
Ba	484	532	653	139	776	318	818	917
Ni							24	24
Y	5	3	13	8	26	8	57	57
Zr	207	150	296	190	698	358	343	310
Nb	2	2	6	4	15	4	19	21

A Mean of quartzites from Eilde Flags (12 analyses, SiO_2 90%) (Hickman, 1972)

B Mean of psammites from Eilde Flags (34 analyses, SiO_2=75-90%) (Hickman, 1972)

C Mean of semi-psammites from Eilde Flags (24 analyses, SiO_2=65-75%) (Hickman, 1972)

D 'Type' Leven Schist (Lambert, et al., 1982, Table 1)

E Leven Schist from Glen Roy (Lambert, et al., 1982, Table 1)

ANALYSES FROM THE EILDE FLAGS AND THE LEVEN SCHISTS.

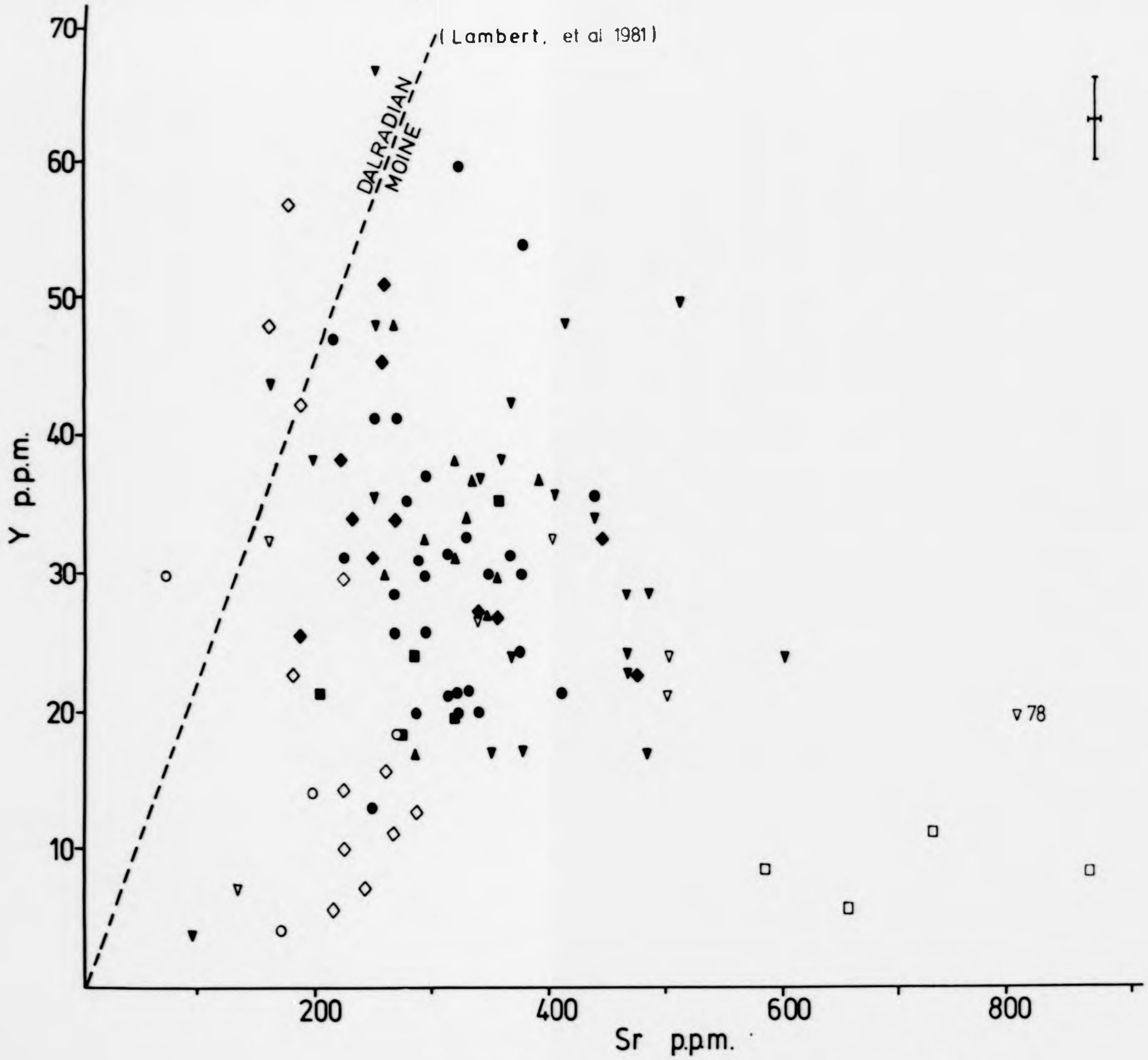


Figure 4.14: Y v. Sr (Key as for figure 4.2).

Anderson (1956) equated the impersistent quartzites at the base of the Monadhliath Schist with the Eilde quartzite of the Lochaber region, so lending weight to his correlation between the Leven Schist of Glen Roy and the Monadhliath Schist. It is worthwhile therefore to briefly compare the quartzite analysis with analyses of the Eilde Quartzite from Kinlochleven, quartzites from the Eilde Flags and the Glen Coe Quartzite (Hickman, 1972) (Table 4.2). These comparisons must be rather tentative due to the problem of comparing a single analysis with averages (Albee, 1952).

Sample 101A contains lower concentrations of K_2O, Rb, Ba, Y and Zr, and has a lower Rb/Sr ratio than the Eilde Quartzite. It also has higher concentrations of Sr and Nb, and has higher Ba/Rb, Sr/Y and Nb/Y ratios. These differences are accentuated when this sample is compared with quartzites stratigraphically higher in the Lochaber Subgroup: the Binnein and Glen Coe Quartzites which show an increasing 'Dalradian' character (Lambert, et al., 1981). However quartzites from the Eilde Flags also show dominantly 'Dalradian' characteristics and are significantly different to sample 101A.

The differences suggest that the quartzite from the Corrieyairack area contain a higher ratio of feldspar to clay minerals compared to the rocks to the south. This may be due to a less extended transport or weathering history, or to a different provenance (Section 2c). Although Sample 101A may not be truely representative of the Corrieyairack quartzites on the available evidence it seems unlikely that they are either chemically or stratigraphically equivalent to the quartzites of the Lochaber Subgroup. The distance between the two areas exceeds 50 kilometres and is more than sufficient for the differences to be explained in terms of facies variation. Thus the difference in chemistry does not necessarily mean that the quartzites cannot be equated stratigraphically but merely suggests that this is less probable.

The rocks of the Corrieyairack area are thought to form part of the upper part of the Grampian Division (Piasecki & Van Breeman,1979, Piasecki, 1980) with the Corrieyairack Succession underlying the Dalradian Lochaber Transition Group with apparent conformity (Haselock and Winchester, 1981). However, analyses of the Eilde Flags of the Kinlochleven area (Hickman, 1972), bear little resemblance to either of the two successions in the Corrieyairack area (Table 4.10). For example: the rocks of the Corrieyairack Succession are generally much less SiO_2 rich than the 'Eilde Flags' in which very few samples have a concentration of SiO_2 below 70% and several samples are above 90%. This may be a result of sampling but comparing these figures with the Knockchoilum Semi-psammite, in which only 5 samples out of 30 are above 70% SiO_2 and none reach 90%, would indicate that the Eilde Flags are considerably more quartz rich. For comparitive purposes Hickman's (1972) analyses of the Eilde Flags have been divided according to SiO_2 content into three rock types as discussed in Section 2a : Quartzite, Psammite and Semi-psammite (Table 4.10). There are no analyses of semi-pelites or pelites.

Semi-psammites.

The Corrieyairack Succession has higher concentrations of MnO, P_2O_5, Sr and Nb, and lower concentrations of Zr, than the Eilde Flags resulting in lower K/Rb, Rb/Sr, and higher Sr/Y and CaO/Y ratios. The Glenshirra Succession also has higher P_2O_5 and Nb, and lower Zr, and also higher Rb, K_2O and Ba, resulting in slightly lower Rb/Sr, CaO/Y and higher P_2O_5/Y and Sr/Y ratios but similar K/Rb ratios.

These differences suggest that the two successions from the Corrieyairack area represent sediments which had a higher proportion of detrital feldspar than the Eilde Flags, possibly plagioclase in the case of the Corrieyairack Succession (Sr) but also alkali feldspar in the case of the Glenshirra Succession (Rb, K_2O and Ba). This may be due to differences in the weathering history and distance from the source area, particularly considering that the two areas are separated by a distance in excess of 50 kilometres. The differences in MnO, P_2O_5 and Nb may indicate a different provenance for the Corrieyairack rocks, P_2O_5 being controlled by detrital apatite and Nb and Mn by detrital oxide phases.

Psammites.

Compared with psammites from the Eilde Flags, the Corrieyairack Succession psammite has higher MnO, CaO, Na_2O, P_2O_5, Sr and Nb, and lower Al_2O_3, Rb, Ba and substantially lower K_2O. The Glenshirra Succession has slightly higher K_2O, P_2O_5, Ba, Rb, Sr and Nb, and lower Zr concentrations but generally has a composition very much closer to that of the Eilde Flags than the Corrieyairack psammite, with very similar K/Rb and Rb/Sr ratios. These differences again suggest a higher proportion of feldspar in the Corrieyairack psammites, with higher plagioclase (Na_2O, CaO, Sr) in the Corrieyairack psammite and higher alkali feldspar in the Glenshirra Succession (K_2O, Ba, Rb, Sr).

Using the criteria of Lambert et al. (1981) rocks from both areas have dominantly 'Moine' type chemistries, although the ratios given are really more applicable to semi-pelitic lithologies. The samples from the Corrieyairack area do show different geochemistries to the Eilde Flags, but the distance between the outcrops, involving the possibilities of major facies variations, means that until the intervening ground has been mapped, the possibility that the two areas are stratigraphically equivalent cannot be eliminated.

The extent to which the differences in chemistry between two areas can be assigned to variations within a single stratigraphic formation, can be assessed to some extent by comparison of analyses of the Monadhliath Semi-pelite along strike:

The Monadhliath Semi-pelite can be traced in a narrow belt, in the core of the Corrieyairack Syncline, from Glen Roy in the south, across the Corrieyairack Pass to Loch Killin and Strath Dearn (Chapters 1 & 2). Analyses from Loch Killin and Coignafearn to the north of the Corrieyairack area (Lambert et al., 1981) (Table 4.11) have higher Al_2O_3, TiO_2 and K_2O concentrations and lower Na_2O, Sr and Nb, and higher Rb/Sr and K/Rb ratios. This indicates a higher proportion of plagioclase in the Corrieyairack area, compared with alkali feldspar. The higher Na_2O/K_2O ratio suggests that the Monadhliath semi-pelite of the Corrieyairack area is a little less 'mature' than the semi-pelite to the northeast, possibly indicating that the detrital material is derived from a southerly or westerly direction.

Hickman (1975) also recorded a southerly increase in feldspar content in Lochaber Group Quartzites and he also recorded northerly flowing currents suggesting a land mass to the south or west if the currents represent longshore drift. The general increase in maturity of the Dalradian of the Lochaber area compared with rocks lower in the succession in the Corrieyairack area, suggests an overall transgressive sequence with a southward receding landmass, or possibly a different provenance.

As the metasediments of the Corrieyairack Pass area have chemistries characteristic of the Moine Assemblage (Lambert et al.,1981) and have previously been regarded as part of the Moine Assemblage (Johnstone, 1966), it is worthwhile to compare the two successions with analyses from the three divisions of the Moine Assemblage north of the Great Glen Fault (Winchester et al.,1981).

Many of the differences between the two successions and the three divisions can be attributed to the variations in proportion of alkali feldspar, plagioclase and clay minerals. These differences point to

TABLE 4.11: ANALYSES OF MONADHLIATH SCHIST, LEWISIAN GNEISS AND MORAR BASAL PELITE.

	A	B	C	D	E	
SiO_2	59.20	62.73	64.56	66.72	60.10	8.36
TiO_2	.99	.95	.47	.34	.85	.31
Al_2O_3	20.34	19.17	15.74	16.04	17.39	2.83
Fe_2O_3	7.59*	6.70*	2.53	1.94	6.35*	2.93*
FeO			2.00	1.47		
MnO	.13	.09	.06	.04	.09	.04
MgO	2.97	2.04	2.23	1.44	2.24	1.23
CaO	1.99	1.15	4.50	3.18	2.71	1.17
Na_2O	2.43	1.90	4.60	4.90	3.67	1.01
K_2O	4.08	4.85	1.15	2.09	4.29	1.86
P_2O_5	.26	.21	.16	.14	.25	.11
Rb	165	162	13	74	140	87
Sr	302	210	565	580	541	145
Ba	1189	1179	779	713	1207	469
Ni	33	27	37	20	27	31
Y	27	37	8	7	27	13
Cr			48	32	182	112
Zr	189	276	197	193	320	112
Nb	15	16	5	6	11	5

A Monadhliath Schist from Killin (Lambert, et al., 1982, Table 1)

B Monadhliath Schist from Coignafearn (Lambert, et al., 1982, Table 1)

C Mean of 154 Lewisian Gneisses from Assynt (Sheraton, et al., 1973, Table 4)

D Mean of 39 Lewisian Gneisses from Rhiconich (Sheraton, et al., 1973, Table 4)

E Mean of 28 analyses from Morar Basal Pelite (Winchester, pers. comm.)

* Total Fe as Fe_2O_3

slightly different conditions of deposition and weathering of the original sediments as would be expected from sediments separated by fairly considerable distances. However, some of the differences may indicate variations in provenance, which are more important when considering regional stratigraphic correlations.

Plots of K_2O/Na_2O v Rb/Sr (Fig 4.15) used by Lambert et al. (1981) to distinguish between semi-pelites from the three Moine Divisions and the Appin Group of the Dalradian, show a general increase in the 'chemical maturity' of the sediments from the Morar Basal Pelite to the Eilde Schist. The mean value for semi-pelites from the Corrieyairack Succession plots close to the means for the Morar Basal Pelite and Morar Pelite. Whereas the Glenshirra Succession semi-pelite plots above the Glenfinnan Division. This may be due to a high alkali feldspar content of the Glenshirra Succession rather than an increase in the maturity of the sediment. A similar relationship can be seen on a plot of Rb/Sr against CaO (Fig 4.15) (Lambert et al.,1981) and in a plot of Sr/Y with SiO_2 (Fig 4.16), where both successions plot in the field occupied by the Morar and Glenfinnan Divisions.

Semi-pelites from the Corrieyairack Succession have higher concentrations of MnO, Ni and Nb, and lower concentrations of Cr and Zr than the Morar Pelites (Table 4.12) but otherwise have very similar chemistries. The differences in these trace elements may reflect either a source control or differences in sedimentary environment resulting in different degrees of adsorption of the trace elements by the clay minerals present.

The Glenshirra Succession is also fairly similar in composition to the Morar Division (Table 4.12) but again the higher proportion of original alkali feldspar in the Glenshirra Succession is reflected by higher K_2O, Rb and Ba concentrations, and higher Rb/Sr ratios. The succession also

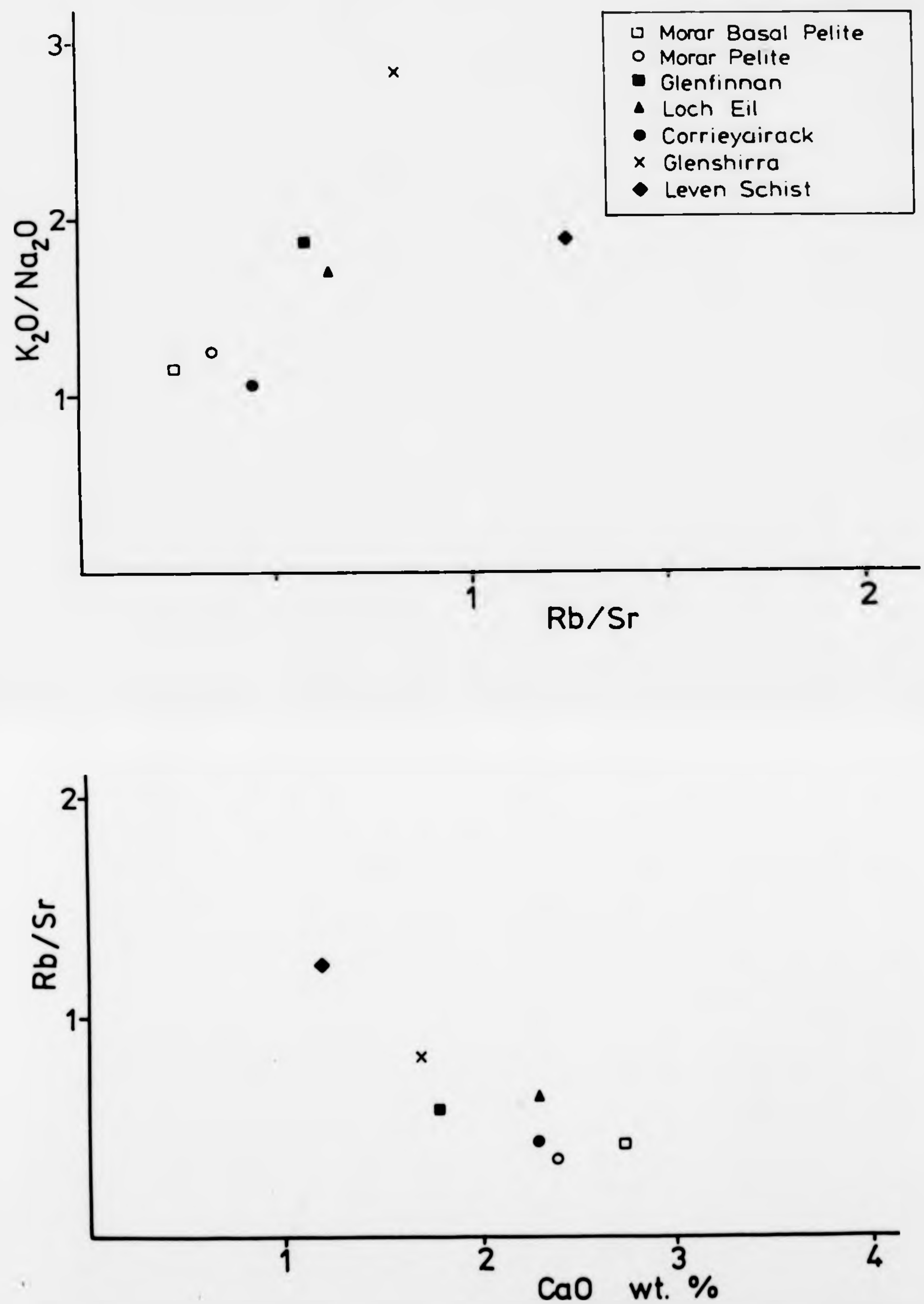


Figure 4.15: a) K_2O/Na_2O v. Rb/Sr, b) Rb/Sr v. CaO for averages of Moinian semi-pelites, Leven Schists, Corrieyairack Succession and Glenshirra Succession, from Lambert, et al. (1980).

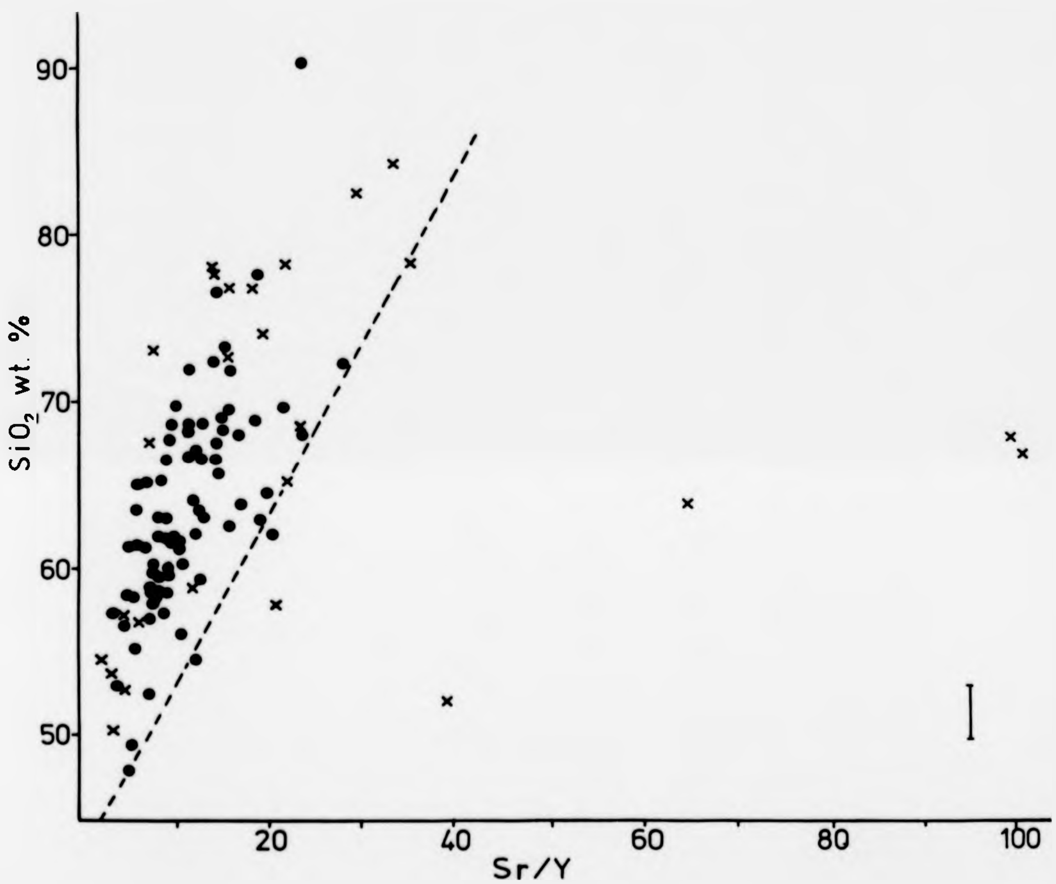


Figure 4.16: SiO_2 v. Sr/Y. Dashed line represents approximate boundary of Basal Morar Pelite compositional field (below line), from Winchester, et al. (1981). Corrieyairack Succession (●), Glenshirra Succession (×).

TABLE 4.12

	A	B	C		D		E		F	
SiO_2	75.52	62.68	60.34	4.52	77.35	4.79	64.70	5.49	78.73	6.48
TiO_2	.61	.94	1.08	.20	.61	.39	1.04	.31	.49	.26
Al_2O_3	11.44	17.12	18.80	2.54	11.06	2.73	16.10	3.39	10.76	2.95
Fe_2O_3	3.03	6.62	7.50	1.33	3.12	1.12	5.79	2.11	2.25	1.15
MnO	.06	.09	.10	.02	.07	.03	.10	.04	.06	.05
MgO	.79	2.14	2.36	.41	.88	.41	1.82	.78	.67	.41
CaO	1.31	2.38	1.77	.87	1.56	.87	2.27	.76	1.73	.99
Na_2O	2.34	2.92	2.51	1.35	2.43	.81	2.73	1.04	2.63	1.08
K_2O	4.01	3.67	4.69	1.56	2.39	1.22	4.57	1.70	2.45	1.02
P_2O_5	.14	.28	.23	.10	.10	.07	.23	.15	.08	.07
Rb	124	138	173	52	66	33	184	79	93	39
Sr	300	396	296	154	290	127	287	106	250	105
Ba	895	949	1035	352	628	124	991	351	594	335
Ni	8	22	30	8	15	6	20	9	9	7
Y	20	37	40	9	21	13	51	16	29	15
Cr	116	175	74	42	30	28	55	21	24	10
Zr	289	303	260	103	273	124	500	209	374	323
Nb	10	15	20	4	13	5	23	3	14	6

A Mean of 68 analyses of Morar Psammite (Winchester, pers. comm.)

B Mean of 55 analyses of Morar Pelite, excluding Basal Pelite (Winchester, pers. comm.)

C Mean of 22 analyses of Glenfinnan pelites (Winchester et al., 1981)

D Mean of 16 analyses of Glenfinnan psammites (Winchester et al., 1981)

E Mean of 6 analyses of Loch Eil pelites (Winchester et al., 1981)

F Mean of 31 analyses of Loch Eil psammites (Winchester et al., 1981)

ANALYSES FROM THE WESTERN MOINES.

has lower CaO/Y and Sr/Y in the semi-pelites indicating either a higher proportion of original clay minerals or the relative lack of plagioclase, and higher MnO, MgO, Ni and Nb possibly reflecting a more basic source, or more rapid deposition, retaining a higher proportion of the relatively unstable mafic minerals in the sediment.

The Corrieyairack Succession rocks also appear to have had a higher proportion of feldspar, particularly plagioclase, to clay minerals than the Glenfinnan Division (Table 4.12) with lower concentrations of K_2O, higher Sr/Rb, CaO/Y, Sr/Y ratios and lower K_2O/Na_2O, K/Rb, Ba/Rb ratios. The Glenshirra Succession in contrast, is very similar in composition to the Glenfinnan Division, apart from a higher K_2O concentration. This is attributed to higher alkali feldspar in the original sediment either due to a different provenance or due to differing weathering and transport histories.

Compared with the Loch Eil Division (Table 4.12) the chemistry indicates that both successions are slightly less 'mature', with a higher proportion of feldspar to clay minerals. All rock types from both successions have a higher Sr/Y ratio. The Corrieyairack Succession has higher K/Rb, Ba/Rb and CaO/Y ratios, and lower Rb/Sr and K/Na ratios, whilst the Glenshirra Succession has higher K/Na and lower CaO/Sr in both rock types , and higher K/Rb, Ba/Rb and Ca/Y in the psammitic lithologies.

The metasediments of the Corrieyairack Pass area, therefore seem to be more comparable in composition with the Morar and Glenfinnan Divisions than the Loch Eil Division, but in view that this is a result of the comparison of mean values of small numbers of samples, which may not be truly representative, and also the different structural and metamorphic histories of the three divisions, no stratigraphic correlations can be assumed and the geochemistry can only indicate similarities in sediment type rather than suggesting that any of the rock groups are equivalent.

3. BIOTITE CHEMISTRY AND OTHER MINERALOGICAL VARIATIONS

The study of the mineralogy of the metasediments from the Corrieyairack area revealed the presence of two contrasting types of biotite. Those from the Corrieyairack Succession are characteristically pleochroic from red brown to straw yellow, whist those from the Glenshirra Succession are pleochroic from olive green to dark green (Chapter 3).

As these differences were consistent between the successions a selection of the biotites were separated and analysed, in an attempt to explain the variation in terms of the chemistry of the biotites and to relate this to the whole rock composition.

Twelve samples were analysed: five samples of green biotite from the Glenshirra Succession, three samples of red biotite from the 'migmatitic' Coire nan Laogh Semi-pelite and four samples from the rest of the Corrieyairack Succession. The biotites were analysed by wet chemical techniques for ten major elements (details of separation and analytical techniques can be found in Appendix A). The structural formulae were calculated on the basis of 22 oxygens (Barth, 1952) as fluorine was not determined and H_2O was approximated from the loss on ignition (Table 4.13).

The principal difference in chemistry between the biotites from the two successions is the oxidation state of the iron. The green biotites of the Glenshirra Succession have a higher ratio of Fe_2O_3/FeO than the red biotites of the Corrieyairack Succession. The biotites fron the Coire nan Laogh 'Migmatitic' Semi-pelite appear to be transitional between the two successions with intermediate values for Fe_2O_3/FeO although they are closer to the Corrieyairack type and retain the red brown colour characteristic of the Corrieyairack Succession. The total iron content is fairly constant between the two successions (Fig 4.17).

TABLE 4.13: ANALYSES OF BIOTITES.

Sample no.	263	7867	7869	78	155	244	107	281	206B	180	171	191
SiO_2	36.26	36.79	36.06	36.09	36.81	35.32	32.63	36.13	35.78	35.58	37.55	35.68
TiO_2	2.50	3.01	3.09	4.56	2.69	2.03	5.70	2.31	2.17	3.03	2.71	2.87
Al_2O_3	18.39	20.04	19.22	14.93	18.98	19.57	19.09	19.29	18.34	17.82	18.32	18.21
Fe_2O_3	4.81	3.46	3.13	3.91	6.18	2.72	2.59	2.75	.84	2.23	1.43	1.75
FeO	16.57	17.04	17.09	15.65	14.21	18.82	20.49	17.89	20.64	19.81	18.25	19.94
MnO	.49	.39	.36	.46	.84	.17	.31	.17	.33	.21	.10	.25
MgO	7.79	6.36	7.48	10.95	9.67	7.96	7.44	8.74	8.20	8.37	7.97	7.88
CaO	.00	.04	.03	.58	.00	.00	.08	.00	.38	.55	.17	.35
Na_2O	.48	.70	.63	.52	.51	.53	.51	.54	.55	.62	.71	.53
K_2O	8.40	9.48	9.75	8.27	9.20	8.37	7.47	8.4C	8.30	6.87	8.45	8.44
L.O.I	4.57	3.25	3.30	3.28	3.63	4.47	4.10	3.83	4.26	4.98	4.11	4.24
Total	100.26	100.56	100.14	99.20	102.72	99.96	100.41	100.05	99.79	100.07	99.06	100.14

263: Carn Dearg Psammite

7867: Creag Mhór Psammite (Average of 2 analyses)

7869: Creag Mhór Psammite

78: Allt Luaidhe Semi-psammite

155: Creag Mhór Psammite

244: Coire nan Laogh Semi-pelite (Migmatitic)

107: Coire nan Laogh Semi-pelite (Migmatitic)

281: Coire nan Laogh Semi-pelite (Migmatitic)

206B: Knockchoilum Semi-psammite.

180 : Tarff Gorge Semi-pelite.

171: Monadhliath Semi-pelite

191: Monadhliath Semi-pelite

Sample no.	263	7867	7869	78	155	244	107	281	206B	180	171	191
Si	5.47	5.46	5.40	5.44	5.34	5.36	4.97	5.41	5.46	5.42	5.63	5.42
Al	2.53	2.54	2.59	2.56	2.66	2.64	3.03	2.59	2.54	2.58	2.37	2.58
Al	.73	.96	.79	.09	.59	.86	.40	.81	.76	.62	.87	.68
Ti	.28	.33	.35	.52	.29	.23	.65	.26	.24	.35	.30	.33
Fe^{3+}	.54	.39	.35	.44	.67	.31	.30	.31	.10	.25	.16	.20
Fe^{2+}	2.09	2.11	2.14	1.97	1.72	2.39	2.61	2.24	2.63	2.52	2.29	2.53
Mn	.06	.04	.04	.06	.10	.02	.04	.02	.04	.03	.01	.03
Mg	1.75	1.41	1.67	2.46	2.09	1.80	1.69	1.95	1.86	1.88	1.78	1.78
Ca	.00	.01	.01	.09	.00	.01	.01	.00	.06	.09	.03	.06
Na	.14	.20	.18	.15	.14	.15	.15	.16	.16	.18	.21	.16
K	1.62	1.79	1.86	1.59	1.70	1.62	1.45	1.60	1.61	1.33	1.62	1.64

TABLE 4.14: ANALYSES OF BIOTITES, CATIONS ON THE BASIS OF 22 OXYGEN.

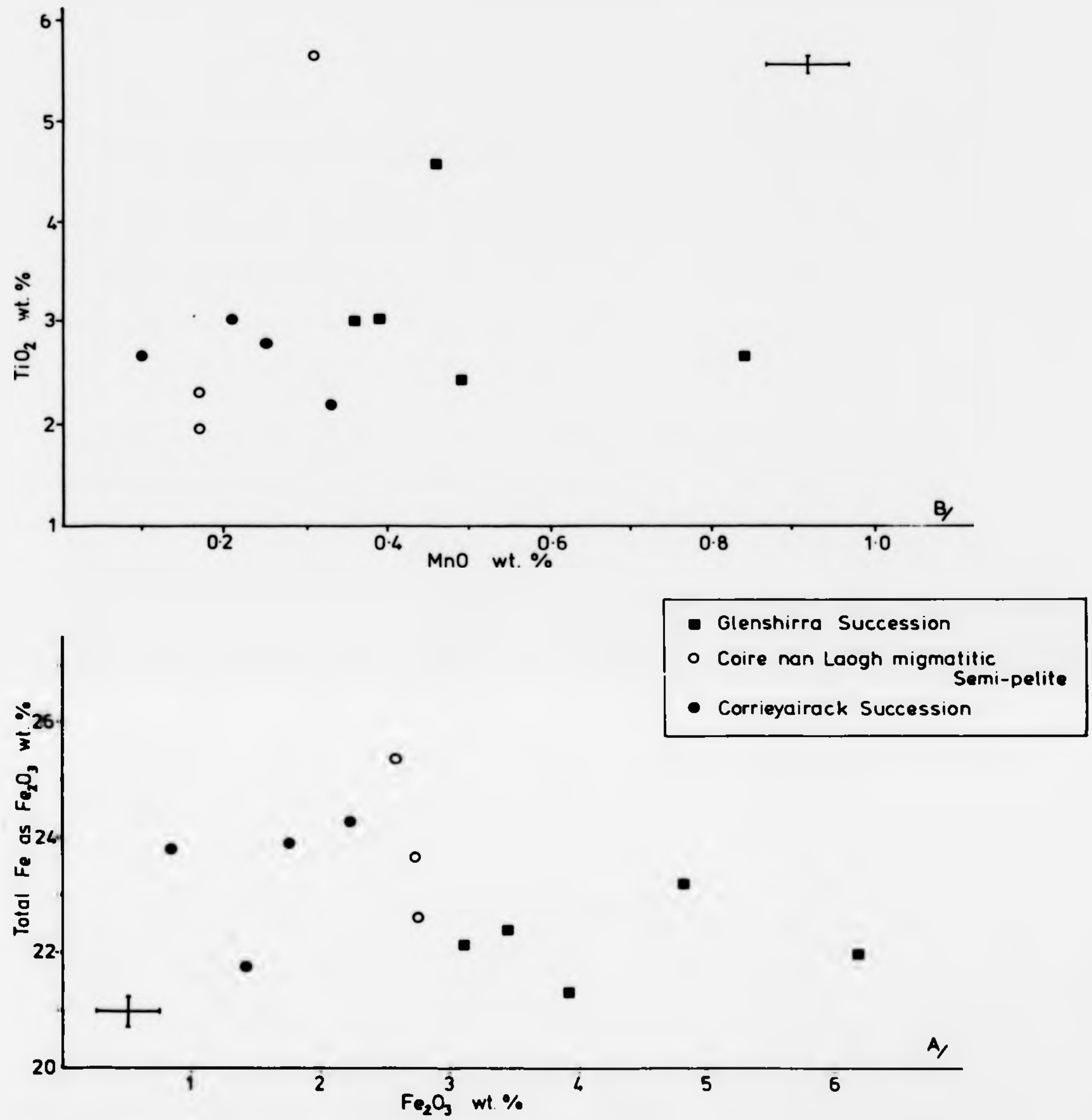


Figure 4.17: a) Fe_2O_3 total v. Fe_2O_3, b) TiO_2 v. MnO for biotites from the Corrieyairack Pass area.

The Glenshirra biotites also have higher concentrations of MnO and K_2O (Fig 4.17 & 4.18). TiO_2 concentrations are variable but there is no consistent difference between the two successions. There is also no differentiation between the successions on the basis of Al_2O_3 and MgO conccentrations (Fig 4.19).

Many attempts have been made to relate the colour of biotites to their chemistry and environment of formation. Tilley (1926) and Hanker (1932) related the brownish colour to high FeO and Grout (1924) stated that Fe_2O_3 produced a greenish tinge. Hall (1941) considered that the colour of the biotite depended on TiO_2, total Fe and MgO, the TiO_2 producing a reddish tinge which is diluted by MgO, and the green colour a result of high total iron. Hayama (1959) also thought that the biotite colour depends mainly on TiO_2 and the ratio Fe_2O_3 to total Fe. Engel and Engel (1960) recognised a systematic change in colour from 'greenish brown' through 'reddish brown' to 'deep reddish black' with increasing metamorphic grade. They thought this was due to the ratios TiO_2 : MgO : total Fe, with MgO again acting as a diluting agent to the colour effects of Fe and TiO_2. They indicated, however, that the composition of the biotites was clearly related to the nature of the other ferromagnesium minerals present and the whole rock chemistry as well as the metamorphic grade. They noted many examples of a change in colour of the biotites from greenish brown to red or reddish brown with progressive metamorphism and the appearance of almandine garnet, where partitioning of Fe and Mg between garnet and biotite results in a decrease of Fe in the biotites relative to MgO and TiO_2.

Decreasing Fe^{2+}, MnO and Fe^{3+} and Fe_2O_3/total Fe, increasing TiO_2 and MgO, and increasing substitution of Al^{3+} for Si^{4+} have also been correlated with increasing metamorphic grade (Lambert,1959, Hayama,1959, Engel and Engel,1960, Snelling,1957).

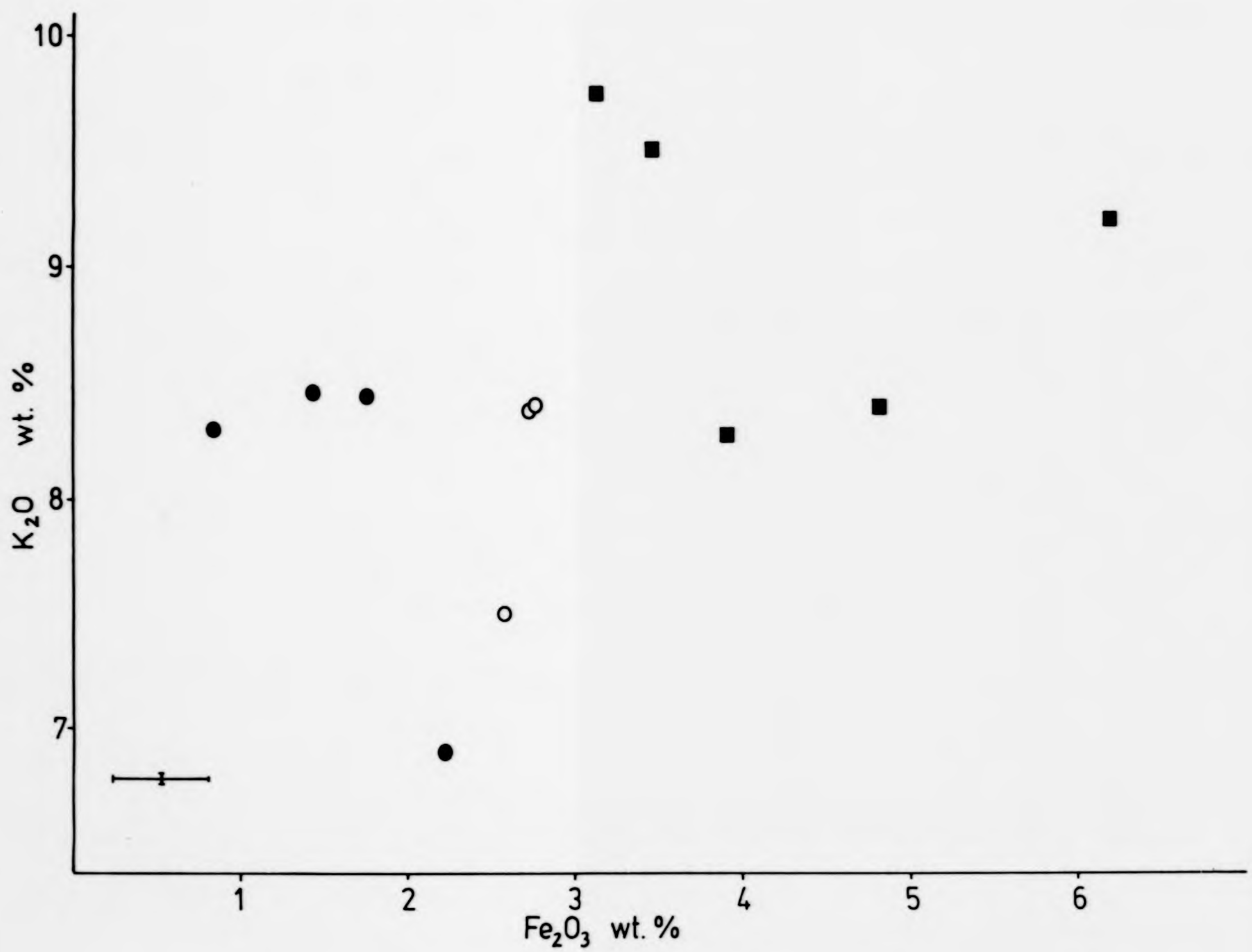


Figure 4.18: K_2O v. Fe_2O_3 for biotites (Key as for figure 4.17).

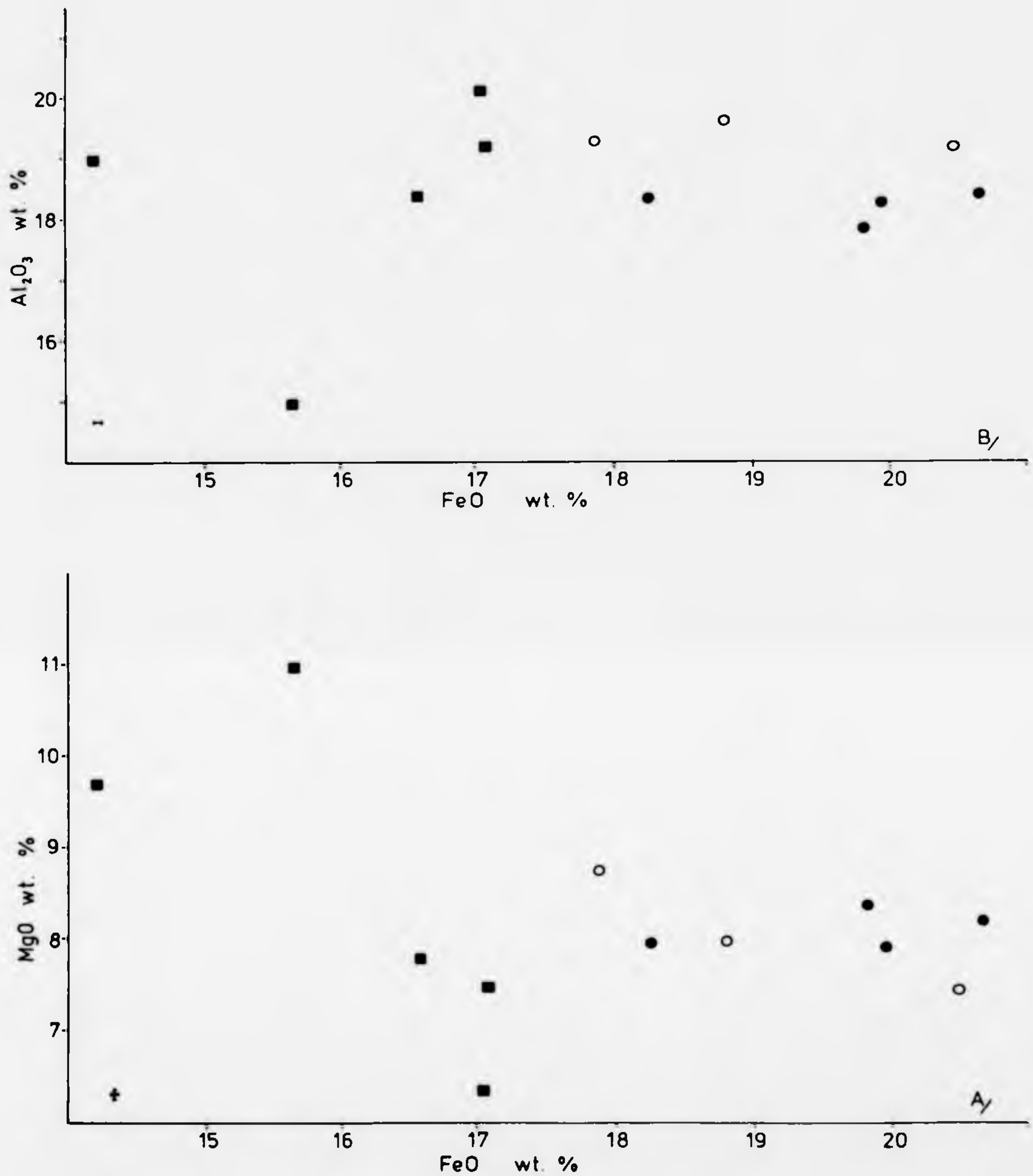


Figure 4.19: a) MgO v. FeO, b) Al_2O_3 v. FeO for biotites(Key as for figure 4.17).

The discussion of the origin of the various colour changes is complicated by the subjectivity of colour estimation and by the large changes in light absorption caused by minor amounts of elements existing in more than one valency state. An initial explanation based on these studies might suggest that the biotites from the Glenshirra Succession are green-brown in colour due to their Fe_2O_3/FeO ratio, and this was a result of the lower metamorphic grade of the succession compared with rocks of the Corrieyairack Succession. At first glance this hypothesis would fit in with the absence of garnet in the Glenshirra Succession and its presence in the Corrieyairack Succession (Chapter 3).

However, the two successions were juxtaposed early in their structural and metamorphic history (Chapter 5) and pelites from both successions contain kyanite as an early phase (Chapter 3). This, together with the presence of late fibrolite in pelites from the Glenshirra Succession nucleating on green biotite with no indication of non-equilibrium, suggests that a difference in metamorphic grade, causing a difference in the oxidation state of the Fe in the biotites, is not the explanation for the colour variation.

If there is a variation in metamorphic grade across the area, the presence of bytownite and pyroxene in calc-silicate bands in the Creag Mhor Psammite would indicate that there is a slight increase in grade to the southeast (Chapter 6), the area occupied by the Glenshirra Succession. Figure 4.20 shows a plot of total Fe v TiO_2/MgO and demonstrated that there is no systematic change in these ratios between the successions. Figure 4.20 shows that the colour of the biotites is not related to the tetrahedrally co-ordinated Al^{3+} or TiO_2, used as indicators of metamorphic grade. MnO is the only indicator of metamorphic grade which behaves as predicted if the Glenshirra Succession is at a lower metamorphic grade than the Corrieyairack (Fig 4.17b).

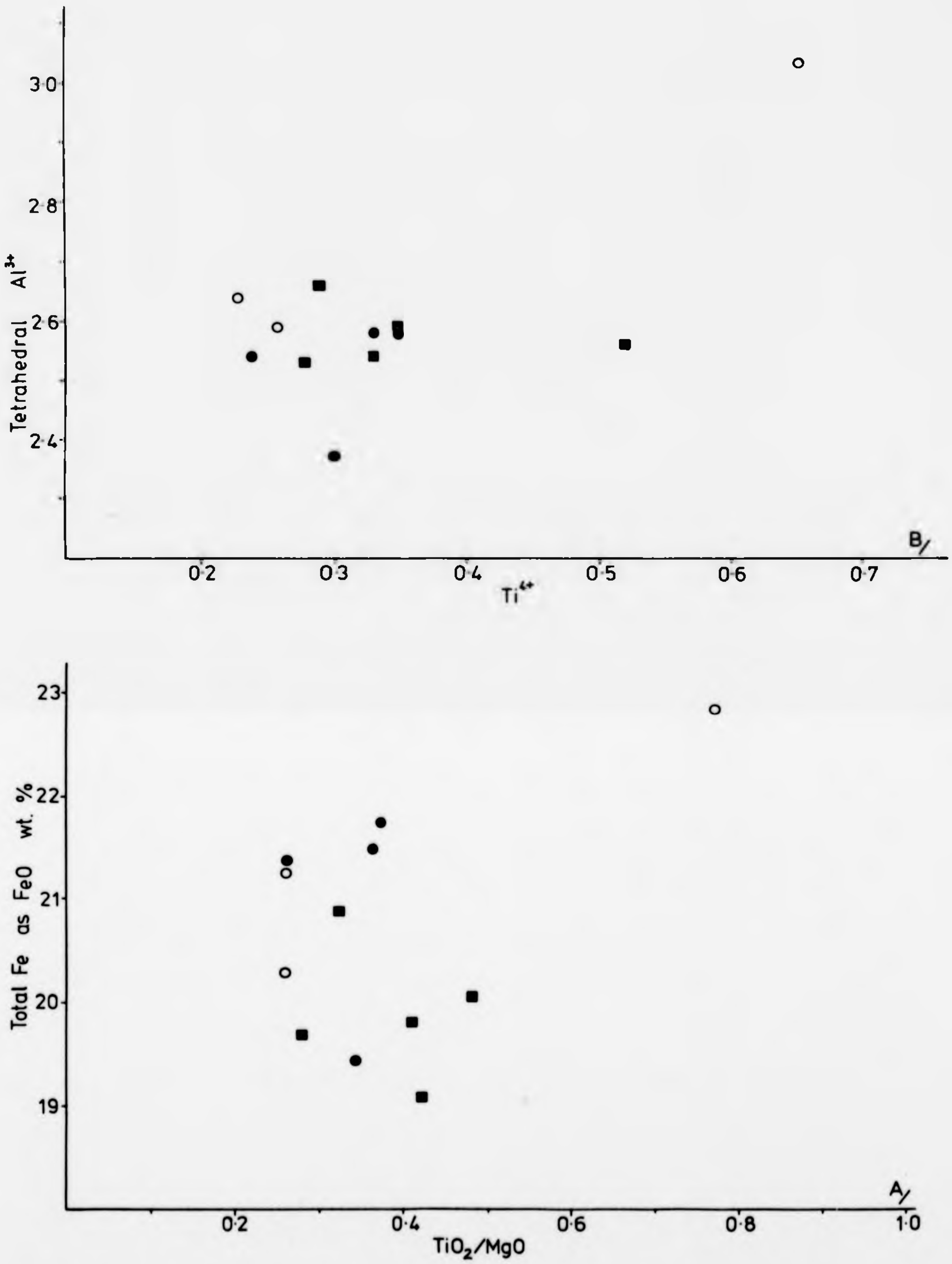


Figure 4.20: a) FeOtotal v. TiO_2/MgO, b) tetrahedral Al^{3+} mol.% v. Ti^{4+} mol.% for biotites. (Key as for figure 4.17).

Chinner (1960) related the colour of the biotite from gneisses in Glen Clova to the opaque phases present. Brown biotite was associated with haematite-free rocks and green biotite associated with haematite-bearing rocks. The green colour was explained by a high Fe_2O_3/FeO ratio, although the major compositional change in the biotites was found in the ratio MgO x 100 / MgO + FeO.

These variations he interpreted in terms of the whole rock oxidation ratio:

$$O.R. = \text{mol } \frac{2Fe_2O_3 \times 100}{2Fe_2O_3 + FeO}$$

Rocks with a low O.R. contained ilmenite-magnetite assemblages and red-brown biotite, and rocks of high O.R. contained magnetite-haematite assemblages and green biotite.

Chinner found a close correlation between Total Fe as Fe_2O_3 in biotites and the O.R. of the whole rock, and suggested that the variations in O.R. were a result of varying total Fe concentrations. During diagenesis a fixed amount of Fe was reduced throughtout the sequence, so that a lower total Fe concentration resulted in a lower O.R.

However, Figure 4.21 shows that there is a very poor correlation between total Fe and O.R. for the rocks of the Corrieyairack area. Rocks of the Corrieyairack Succession group comparatively closely about O.R. = 20 (range 14-32) independent of total Fe, the exception being rocks of the Coire nan Laogh Migmatitic Semi-pelite, where the variation is possibly explained by enhanced fluid migration and abnormal oxidising conditions during migmatization. In contrast, rocks of the Glenshirra Succession, show a large scatter of O.R. with poor correlation with total Fe, stratigraphic formation or distance from the major intrusions.

Similarly, rocks of the Corrieyairack area do not show a close

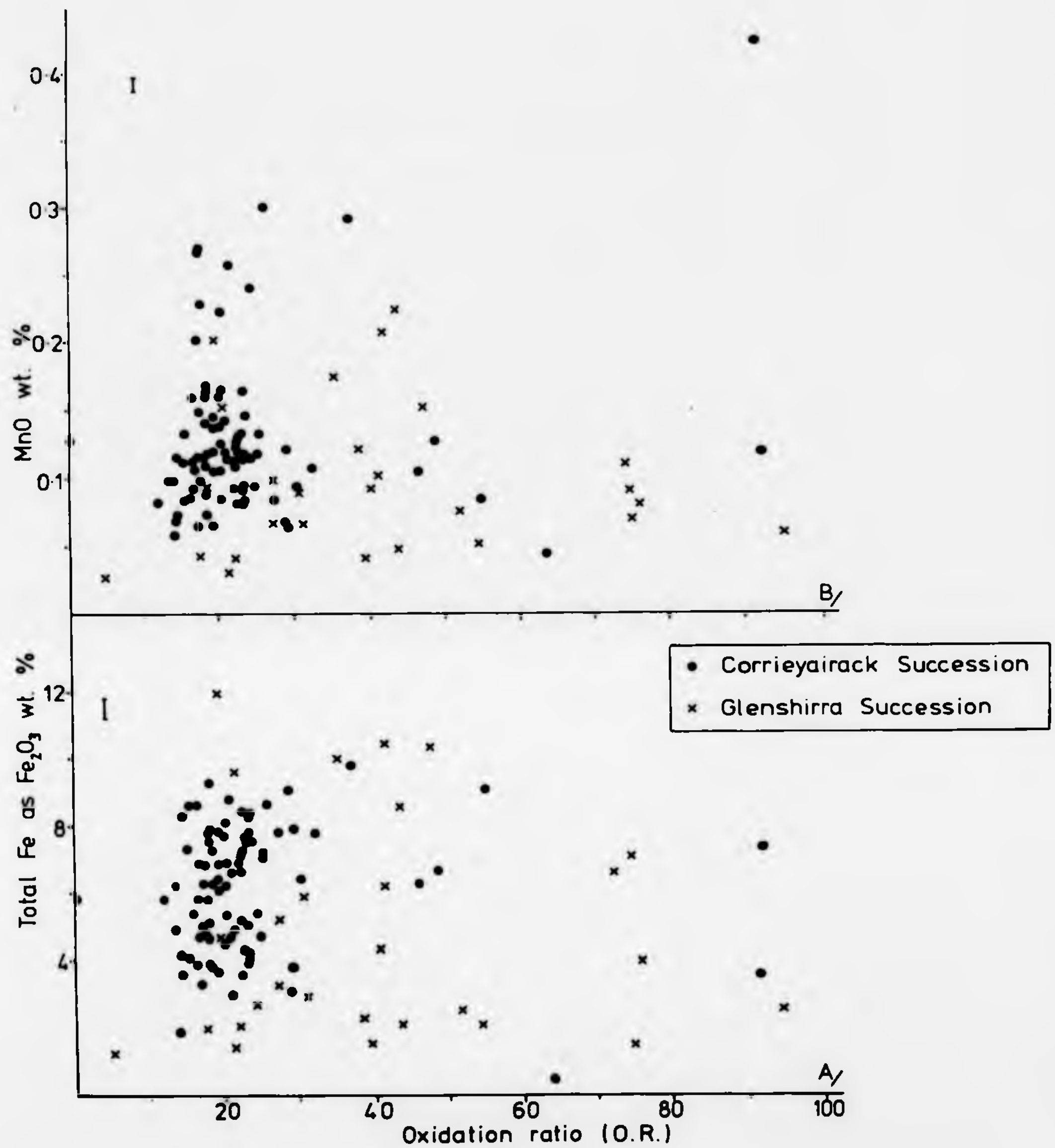


Figure 4.21: A) Fe_2O_3 v. Oxidation Ratio, B) MnO v. Oxidation Ratio for whole rock, after Chinner (1960).

correlation between MnO and O.R. in contrast to the pelitic gneisses of Glen Clova (Fig 4.21). Chinner cites these two correlations as supporting evidence for the premetamorphic origin for the oxidation ratio, and that individual layers were 'closed' to oxygen during subsequent metamorphism; a model supported by Peikert (1963) who investigated biotite variation in granitic rocks.

Comparison of the averages for the various rock types from the two successions do however show that the Glenshirra Succession tends to have a higher Fe_2O_3/FeO ratio than the Corrieyairack Succession and this is also shown on a plot of Fe_2O_3 v FeO (Fig 4.11).

As with the pelitic gneisses from Glen Clova, the Glenshirra Succession rocks contain haematite and magnetite and green biotite, whereas the rocks from the Corrieyairack Succession lack haematite but contain graphite. The presence of graphite under normal conditions of metamorphism leads to a low oxygen pressure, will keep Fe_2O_3 low and stabilize minerals such as almandine whose existence depends on low oxygen fugacity (Muller and Schneider, 1971).

The original carbon content of the sediment is related to processes prevailing during diagenesis and metamorphism. Graphite formation starts only above 200^{o}C and results in the CO_2 partial pressure making up a considerable portion of the total pressure. At low grades of metamorphism oxygen fugacity decreases with increasing pressure and temperature. Haematite and magnetite result from high oxygen partial pressure, but as soon as the temperature is high enough to permit the reaction between graphite and the fluid phase, the partial pressure of oxygen drops and the activity of Fe^{2+} increases (Muller and Schneider, 1971).

The variation in mineralogy between the two successions could therefore be explained by the variation in carbon content of the original sediment. The graphite rich Corrieyairack Succession had a low oxygen fugacity stabilizing garnet and Fe^{2+} rich, red biotites, and the graphite free, Glenshirra Succession maintained a higher oxygen fugacity during metamorphism producing garnet free rocks with Fe^{3+} rich green biotites.

However, many of the Corrieyairack semi-psammites do not contain graphite but still have red brown biotites indicating low oxygen fugacity and occasionally contain garnet. The whole rock composition must be the determining factor in garnet formation and the presence or absence of garnet may in turn effect the Fe^{2+} content of the biotite.

Senior and Leake (1978) discussed the variations in chemistry between garnetiferous and non-garnetiferous pelites from Connemara. The garnetiferous pelites were significantly higher in FeO (7.33 cf.5.49%), CaO (1.63 cf.1.02%), MnO (0.18 cf.0.12%) and poorer in Fe_2O_3 (1.98 cf.3.01) and K_2O (3.42 cf.3.92) than the non-garnetiferous pelites. They concluded that FeO, CaO and MnO are important in determining the presence of garnet as they are essential constituents, whereas Fe_2O_3 and K_2O are absent or present in only small amounts. Jones and Galway (1965) similarly showed that the total content of garnet was proportional to the quantity of free ferrous oxide (assuming the reaction $FeO + Fe_2O_3 \rightarrow Fe_3O_4$ has gone to completion) and that the number of garnet nuclei present was proportional to K_2O and Na_2O, both of which stabilize biotite.

The higher K_2O contents of the Glenshirra Succession would therefore stabilize alkali feldspar and biotite, and inhibit the nucleation of garnet. In the absence of garnet the MnO present in the rock would enter the biotite and thus explain the higher MnO contents in the biotites from the Glenshirra Succession.

The variation in mineralogy between the two successions is therefore thought to be due to original geochemical sedimentary differences. These are principally the oxidising conditions of the sediment, graphite in the Corrieyairack Succession possibly indicating anaerobic conditions in contrast to the more oxidising conditions in the Glenshirra Succession; conditions that were maintained throughout the metamorphic history. The presence of higher concentrations of K_2O in the Glenshirra Succession inhibits garnet formation, K_2O was possibly present as alkali feldspar and the more arkosic nature of the sediment discussed earlier is consistent with the higher oxidising conditions.

4. STATISTICAL ANALYSIS

a. Introduction

Multivariate statistical analysis of the geochemistry of the Corrieyairack Pass area has been undertaken in order to test statistically whether geochemistry can be used to effectively discriminate between the two successions and nine formations recognised in the field (Chapter 2).

The comparison of means and standard deviations and inspection of the two dimensional variation diagrams undertaken in the preceding sections provides some idea of the differences involved but gives no indication of whether the differences between the various groups are real or purely a fortuitous effect of sampling. The problem of closure, or the constant sum of geochemical data, may lead to the suppression of variations between populations when data is plotted on variation diagrams, particularly where ratios of elements are plotted or on triangular diagrams (Skala, 1979). The dominance of SiO_2 in the analyses may also result in variations other than those of rock type being concealed.

Multivariate statistical analysis is a more effective method of separating populations of geochemical variables (Skala, 1979) and two distinct types of analysis have been undertaken: discriminant function analysis, including analysis of variance, and cluster analysis. The first of these methods provides an objective procedure for determining how effectively samples belonging to two or more previously defined groups can be distinguished from each other, by transforming an original set of variables into a single discriminant score. The derived discriminant function can then be used to classify further samples into one or other of the groups.

Cluster analysis, in contrast, involves the separation of the samples into 'natural groups' without 'a priori' classification by consideration of the distance between samples in multivariate space. In both cases, the variables which are most important in distinguishing between the groups can be recognised and subsequently examined in their geological context.

Most statistical models assume that the variables under consideration are normally distributed and statistically independent. These conditions are usually met in cases where there is a relationship between samples with respect to their calculated variables (Q mode) but in other situations emphasis is placed on the relationship between variables with respect to the samples (R mode). In this case the constant sum nature of geochemical data destroys the potential independence of the variances and covariances upon which elementary correlation theory rests (Skala, 1979). For this reason R mode factor analysis was not undertaken.

b. Principles of Discriminant Analysis.

In discriminant analysis the variables are mathematically combined, in order to find a single dimension which maximises the differences between the groups, as a linear combination or discriminant function of the form:

$$Di = di_1 Z_1 + di_2 Z_2 + \ldots\ldots. + di_p Z_p$$

where Di = the score on the discriminant function i

d = weighting coefficients

Z = standardised values of the p discriminating variables.

The maximum number of functions that can be derived is either one less than the number of groups or equal to the number of discriminating variables if there are more groups than variables. The weighting coefficients in a standardised discriminant function show how much each of the variables contribute to the overall discrimination.

Once a set of variables is found which provides satisfactory discrimination for samples from known groups, a set of classification functions can be derived which can be used to classify unknown samples. This procedure can also be used as a check of the adequacy of the discriminant function by classifying the original data set and examining the number of correct classifications.

More detailed discussions of discriminant analysis can be found in Davis (1973), Koch and Link (1971), Cooley and Lohnes (1962) and Anderson (1958).

The method assumes that the variances within the groups are equal and correlations between variables are the same in each group ie. the groups have equal covariance matrices.

While the discriminant function derived from all the variables may effectively distinguish between groups, it does not necessarily give the best discrimination, since all the variables may not be needed to separate the groups. The smaller the number of variables that need to be studied to classify effectively an unknown sample the better (Potter, Shimp and Witters, 1963). Moreover, the elimination of variables that contribute little to the discrimination is desirable since their presence may detract from effectiveness of the functions. This commonly is because variables with a high variability obsure the information contributed by those with low variability.

Discriminant analysis on the metasediments of the Corrieyairack Pass area was performed using the routines from the Statistical Package for Social Sciences (SPSS Nie et al.,1975) available at the University of Manchester (UMRCC). This program utilises a stepwise method which selects the optimal combination of variables for the most effective discrimination, so eliminating variables which do not contribute to the discrimination.

The use of the same data to derive the function and to test its effectiveness in the classification phase results in an upward bias to the percentage of correct classifications (Morrison, 1969, Habbema & Hermans, 1977). A better method of testing the efficiency of the derived function involves the use of part of the data to calculate the function and the rest of the data set to test its efficiency in the classification phase. This is possible in the S.P.S.S. program by assigning random numbers to the samples and selecting 60% of the data for analysis.

The Glenshirra Succession is represented by more psammitic rocks than the Corrieyairack Succession, and although this shows a difference in sediment type or environment of deposition, it does not have any significance in terms of correlating the two successions. Therefore in order to minimise the effects of SiO_2 in the discriminant analysis, the data was divided into two sets according to rock type. Discriminant analysis was then performed on three different data sets:

1. the complete data set, excluding rocks for which trace element data is incomplete (105 samples)
2. psammites and semi-psammites only (57 samples)
3. semi-pelites only (47 samples)

As there are only six semi-pelite samples from the Glenshirra Succession it was considered that the data set was too small to be divided as described above and the discriminant function was derived from all the semi-pelite samples. Similarly, the complete data sets were used to derive the functions for the nine formations, due to the small number of samples in some of the formations.

c. Analysis of Variance.

i. Successions.

If the separation between the two successions is a good one the geochemical variation between the successions should be high compared with the variation within the successions. This is tested by analysis of variance; firstly for each of the major and trace elements and secondly for the complete geochemical pattern.

The null hypothesis: 'that the means of the two successions are the same' is tested using the univariate F-ratio:

$$F = \frac{A}{W}$$ where A = variation within groups
W = variation between groups

with degrees of freedom, Df.1 = G-1 where G = No. of groups
Df.2 = N-G where N = No. of samples

Table 4.15 gives the F-ratios for the three data sets, with their associated degrees of freedom. These values are compared with the critical value from F tables at 1% significance. If the ratio is equal to or above the critical value the null hypothesis can be rejected and the difference between the successions is significant at the 1% level for individual elements.

It can be seen that there are several significant differences between the successions and it is therefore worthwhile continuing with the discriminant analysis. Among the elements with the largest F-ratios are those elements which were discussed in detail in the preceding sections, particularly K_2O, Ba, Rb and Y representing the variations in feldspars and clay minerals, and Fe_2O_3 and FeO indicating the variations in oxidation state.

For the complete geochemical pattern a multivariate extension of the F-ratio is used called 'Wilk's Lambda' (λ). This can be easily transformed into an F test to test the significance of the differences in the multivariate means.

$$\text{Wilk's Lambda}, \quad = \frac{[W]}{[T]} \quad \text{where } [W] = \text{within groups covariance matrix}, \quad [T] = \text{total covariance matrix}$$

The relevant values for Wilk's Lambda and the approximate F values are given in Table 4.15. The degrees of freedom are dependent on the number of samples.

Some degrees of freedom are lost due to the constraints of constant sum, this will affect the values of Df2 in Table 4.15. However, since large degrees of freedom are involved this will not affect the critical F-ratios to any great extent (Chayes, 1971).

These tests again show that there are significant differences between the two successions.

ii. Formations.

The univariate F-ratios testing the null hypothesis 'that the means of the nine formations are the same' are presented in Table 4.17. The multivariate Wilk's Lambda and F-ratios are shown in Table 4.16. These show that there are significant differences between the formations with Rb, Sr, Ba, K_2O and Y (representing the clay minerals and feldspars) and Fe_2O_3 and FeO (representing the oxidation states of the formations) having the highest ratios.

d. Results of Discriminant Analysis.

i. Successions.

The standardized discriminant functions for each of the data sets are presented in Table 4.18 with the relevant tests of significance. For both the semi-psammites and psammites , and the semi-pelites, all the

TABLE 4.15: ANALYSIS OF VARIANCE BETWEEN SUCCESSIONS.

	A	B	C
SiO_2	3.97	4.68	12.94
TiO_2	0.04	0.03	15.26
Al_2O_3	3.29	1.33	1.98
Fe_2O_3	6.94	5.63	14.89
FeO	20.34	41.36	3.74
MnO	4.49	12.51	13.45
MgO	9.63	16.32	15.17
CaO	9.15	6.50	2.75
Na_2O	2.33	1.38	6.03
K_2O	21.98	16.96	23.57
P_2O_5	12.01	11.11	0.12
Rb	0.47	0.16	25.80
Sr	0.13	0.42	1.45
Ba	21.85	21.81	4.72
Ni	0.22	0.01	15.91
Y	19.87	30.40	0.11
Cr	4.52	15.44	28.56
Zr	0.23	0.55	3.39
Nb	0.97	0.00	0.49
Df.1	1	1	1
Df.2	103	55	45
Crit. F at 1% sig.	7.08	7.31	7.31

A: All samples (105)

B: Psammites and Semi-psammites (57)

C: Semi-pelites (47)

TABLE 4.16a: MULTIVARIATE ANALYSIS OF VARIANCE BETWEEN SUCCESSIONS.

	Wilk's Lambda	Approx. F Ratio	Df.1.	Df.2	Crit. F Ratio at 1% sign.
All samples	0.26	14.34	17	87	2.35
Psammites and Semi-psammites	0.16	11.411	18	38	2.70
Semi-pelites	0.13	9.78	19	27	2.78

TABLE 4.16b: MULTIVARIATE ANALYSIS OF VARIANCE BETWEEN FORMATIONS.

	Wilk's Lambda	Approx. F Ratio	Df.1	Df.2	Crit. F Ratio at 1% sign.
All samples	0.007	3.69	152	592	1.70
Psammites and Semi-psammites	0.001	3.12	152	236	1.70
Semi-pelites	0.001	3.35	114	134	1.70

TABLE 4.17: ANALYSIS OF VARIANCE BETWEEN FORMATIONS.

	A	B	C
SiO_2	2.68	4.58	3.12
TiO_2	3.60	4.98	3.17
Al_2O_3	3.35	3.61	1.44
Fe_2O_3	4.23	3.69	4.95
FeO	3.42	6.06	1.36
MnO	1.16	6.14	2.41
MgO	2.89	3.88	6.49
CaO	2.45	2.07	2.71
Na_2O	2.19	1.92	3.87
K_2O	3.66	3.33	8.55
P_2O_5	2.89	3.63	0.99
Rb	2.09	1.49	17.16
Sr	11.91	16.28	3.48
Ba	6.78	7.80	4.95
Ni	3.31	2.19	7.95
Y	3.65	5.62	1.05
Cr	1.88	3.38	6.32
Zr	2.21	1.46	1.85
Nb	0.88	1.63	0.48
Df.1	8	8	6
Df.2	96	48	40
Crit. F at 1% sig.	2.82	2.99	3.29

A: All samples B: Psammites and Semi-psammites

C: Semi-pelites

TABLE 4.18: STANDARDIZED DISCRIMINANT FUNCTION COEFFICIENTS FOR DISCRIMINATION BETWEEN SUCCESSIONS.

	A	B	C
SiO_2	-5.26	4.54	0.37
TiO_2	0.54	0.50	1.44
Al_2O_3	-2.18	3.21	-1.36
Fe_2O_3	-1.50	1.15	-0.19
FeO	-2.20	0.85	-0.71
MnO	-0.29	-0.68	0.57
MgO	0.61	-0.19	0.36
CaO	-0.30	1.21	-0.83
Na_2O	-0.28	0.28	0.83
K_2O	-3.43	-0.95	1.39
P_2O_5	0.43	-1.10	0.07
Rb	1.12	1.21	1.42
Sr	-0.45	0.28	0.49
Ba	-0.17	-2.36	-0.88
Ni	-0.26	-0.71	0.13
Y	0.32	1.71	-0.75
Cr	-	3.13	1.47
Zr	-0.52	-1.51	-0.13
Nb	-0.12	0.08	-0.12
Eigenvalue	3.388	11.373	6.883
Canonical Correlation	0.878	0.959	0.934
Wilk's Lambda	0.228	0.081	0.127
χ^2	82.828	64.146	73.298
Df.	18	19	19
Significance	0.000	0.000	0.000

A: All samples. B: Psammites and Semi-psammites. C: Semi-pelites elements were included in the analysis and considered to contribute to the overall discrimination, but when considering all the rock types together Cr is considered to be unimportant.

In all cases the stepwise method of analysis selected used the Wilk's Lambda criteria for entry of an element into the analysis. This method involves a multivariate F-ratio for the test of differences between the group centroids. The element which maximises the F-ratio minimises Wilk's Lambda. This test takes into consideration the differences between the group centroids and the homogeneity of the groups. Other selection methods eg. Rao's V statistic and Mahalaonbis distance were tried and gave very similar results.

As each element is entered into the analysis two measures of the overall separation, based on the elements in the equation at this point, are given: the first is Wilk's Lambda and the second Rao's V, both with tests of significance. The sequence in which elements are selected is not necessarily the same as their relative importance as discriminators. This is given by the weighting for each element in the final standardised discriminant function.

Only one discriminant function is derived when considering the differences between the two successions (max. no. of discriminant functions = G-1). The significance or importance of the function is tested in several different ways. The eigenvalues are a measure of the total variance existing in the discriminating variables and when expressed as a percentage of the total gives an easy reference to the relative importance of the function. The canonical correlation is a measure of how closely the function and the 'group variables' are related, another measure of the functions ability to discriminate between the groups. Wilk's Lambda, in this instance, is an inverse measure of the discriminating power of the original variables which has not yet been removed by the discriminant function ie. the larger Lambda the less information remains, Chi-squared is a test of the statistical significance of the function.

In the classification phase the prior probability of group membership under the Baye's decision rule (Nie, et al.,1975) was determined by the size of the groups. The results of classification are given in Table 4.19.

Failure to subdivide the semi-pelite data set into two results in an upward bias to the classification success rate (Morrison,1969, Habberna and Hermans,1977), so that the 100% correct classification is spurious, particularly in view of the small number of samples in the Glenshirra Succession.

Results: Complete data set, all rock types.

As expected SiO_2 has the largest weighting coefficient within the discriminant function (Table 4.18), indicating the more psammitic nature of the Glenshirra Succession. The variation in feldspars and clay mineral proportions outlined in Section 2 is supported by the importance of K_2O, Al_2O_3 and Rb in the function. FeO and Fe_2O_3 are also important in the function indicative of the differences in oxidation state of the original sediments (Section 3). Figure 4.22 shows a plot of the discriminant scores for all the samples giving a visual indication of the separation between the successions. Only four samples plot with the wrong succession and clearly separation by the function is very effective.

Psammites and semi-psammites.

Again SiO_2 is the most heavily weighted in the standardized discriminant function, as an effect of the dominance of semi-psammites in the Corrieyairack Succession. Al_2O_3, Ba, Y and CaO represent the variations

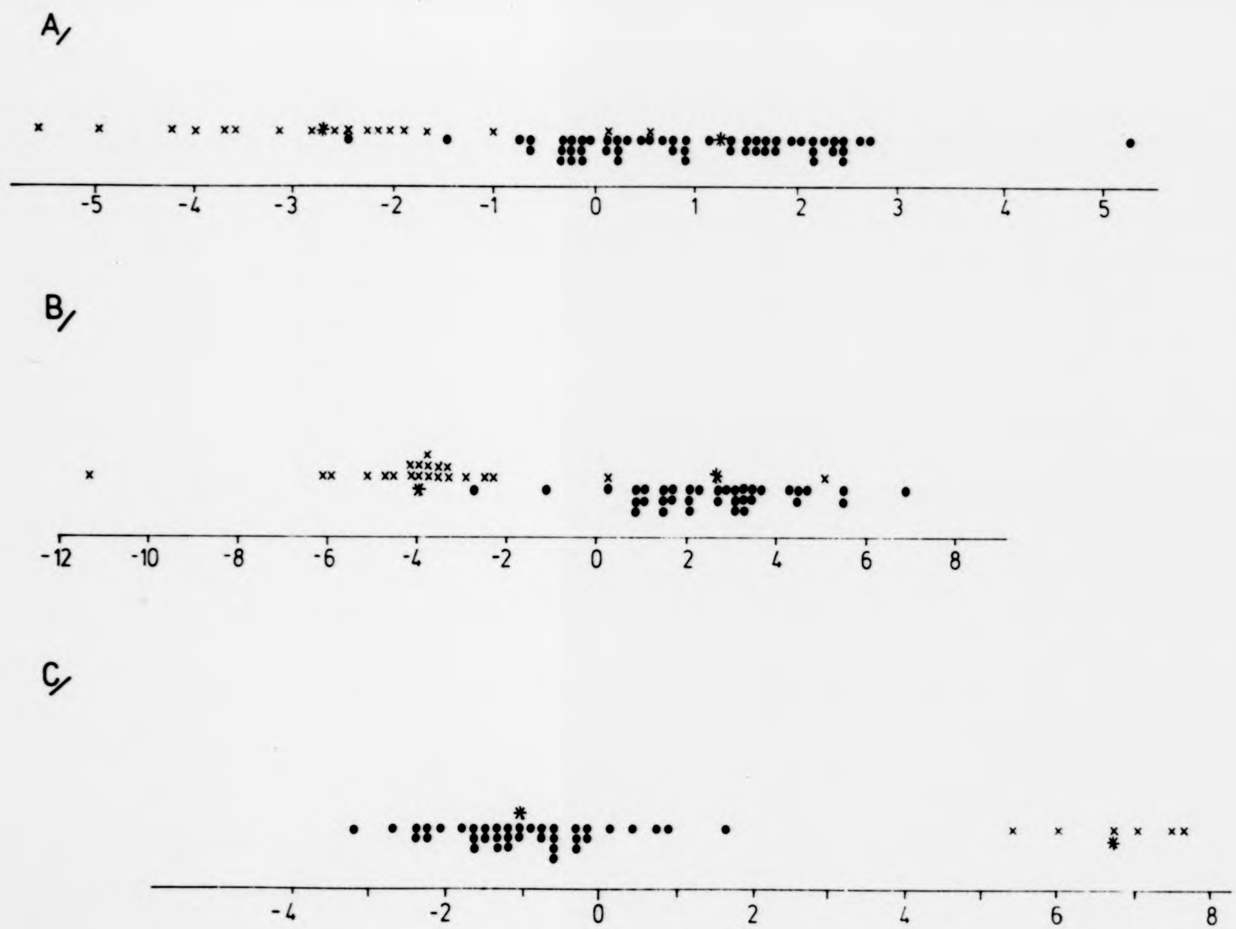


Figure 4.22: Plot of Discriminant Scores A) All samples, B) Semi-psammites and psammites, C) Semi-pelites.

TABLE 4.19: RESULTS OF CLASSIFICATION PHASE: SUCCESSIONS.

	A	B	C
Total no. of samples	105	55	47
No. of samples classified	38	20	47
% correct	95	80	100
χ^2	30.42	7.20	47
Significance	0.00	0.01	0.00
Corrieyairack Succession			
Correct	30	12	41
Incorrect	1	2	0
Glenshirra Succession			
Correct	6	4	6
Incorrect	1	2	0

A: All samples. B: Psammites and Semi-psammites.

C: Semi-pelites

in feldspar and Cr possibly indicates a variation in provenance. Separation of the two successions is again very effective along the discriminant function (Fig 4.22).

Semi-pelites.

The variation of SiO_2 between the semi-pelitic lithologies of each succession is much smaller than between the other rock types and SiO_2 is therefore not as heavily weighted in the discriminant function. The high weightings of Cr and TiO_2 possibly reflects the effects of heavy detrital minerals in turn reflecting variations in sediment provenance. K_2O, Rb, Al_2O_3, Ba and Y are again important, indicative of the clay mineral and feldspar variations. The separation between the successions appears to be extremely good (Fig 4.22) but this is probably an effect of the small number of samples in the Glenshirra Succession. (To be completely satisfactory 75 samples are needed in each group for 8 variables (Pearce,1976) although this is very rarely possible.)

ii. Formations.

Despite there being several significant differences in the means for each formation, indicated by the univariate F-ratios (Table 4.17) and in the multivariate means (Table 4.16), the lack of sufficient data for some of the formations makes the discriminant analysis somewhat artificial.

Attempts to divide the data into a classification or test set and a set to derive the function, resulted in a very poor success rate in the classification phase (41% correct for all rock types and 50% correct for the psammites and semi-psammites). This is because the number of samples in each formation is insufficient to define the variation within each formation. However, in all three analyses very few of the samples were wrongly classified across the successions (Table 4.20).

TABLE 4.20: RESULTS OF CLASSIFICATION PHASE: FORMATIONS.

	All Samples		Psammites/ Semi-psammites		Semi-pelites
Total no. of samples	105	105	57	57	47
No. of samples Classified	105	38	57	19	47
% correct	71.4	42.1	93.0	50.0	95.7
χ^2	386.8	36.9	386.8	30.6	254.7
Significance	0.00	0.00	0.00	0.00	0.00

Using the complete data sets for the derivation of the discriminant function and for the classification resulted in an improvement in the percentage correctly classified but this is probably due to the upward bias discussed earlier (Morrison,1969, Habbema and Hermans,1977). As the first three discriminant functions are significant at the 1% level, it appears that the individual formations could have been distinguished had there been more samples. The results of the analyses are given in Tables 4.20 and 4.21. Figure 4.23 shows the separation of the formations based on the first two discriminant scores for all rock types.

The S.P.S.S. Discriminant Analysis program also prints a matrix of F-ratios as a test of the significance of the Mahalanobis distance between each of the group centroids (Table 4.22). These matrices indicate that several of the groups are separated sufficiently to be distinguished at the 1% significance level, but the remainder are too close. Generally all formations in the Corrieyairack Succession are distinct from those of the Glenshirra. As expected the Gairbeinn Pebbly Semi-psammite is particularly distinctive and can be distinguished from all the other formations.

Semi-pelites from the Tarff Gorge are not distinguishable at the 1% significance level from semi-pelites from the Monadhliath Semi-pelite or the Coire nan Laogh Semi-pelite. The Monadhliath Semi-pelite is however significantly distinct from the Coire nan Laogh Semi-pelite, supporting the field evidence that the two formations are not stratigraphically equivalent.

The discriminant analysis of the metasediments therefore reveals that the differences between the Glenshirra and Corrieyairack Successions are statistically significant and the derived discriminant functions for psammitic and semi-psammitic rocks and for all the rock types together may be useful in classifying unknown samples into one of the two successions.

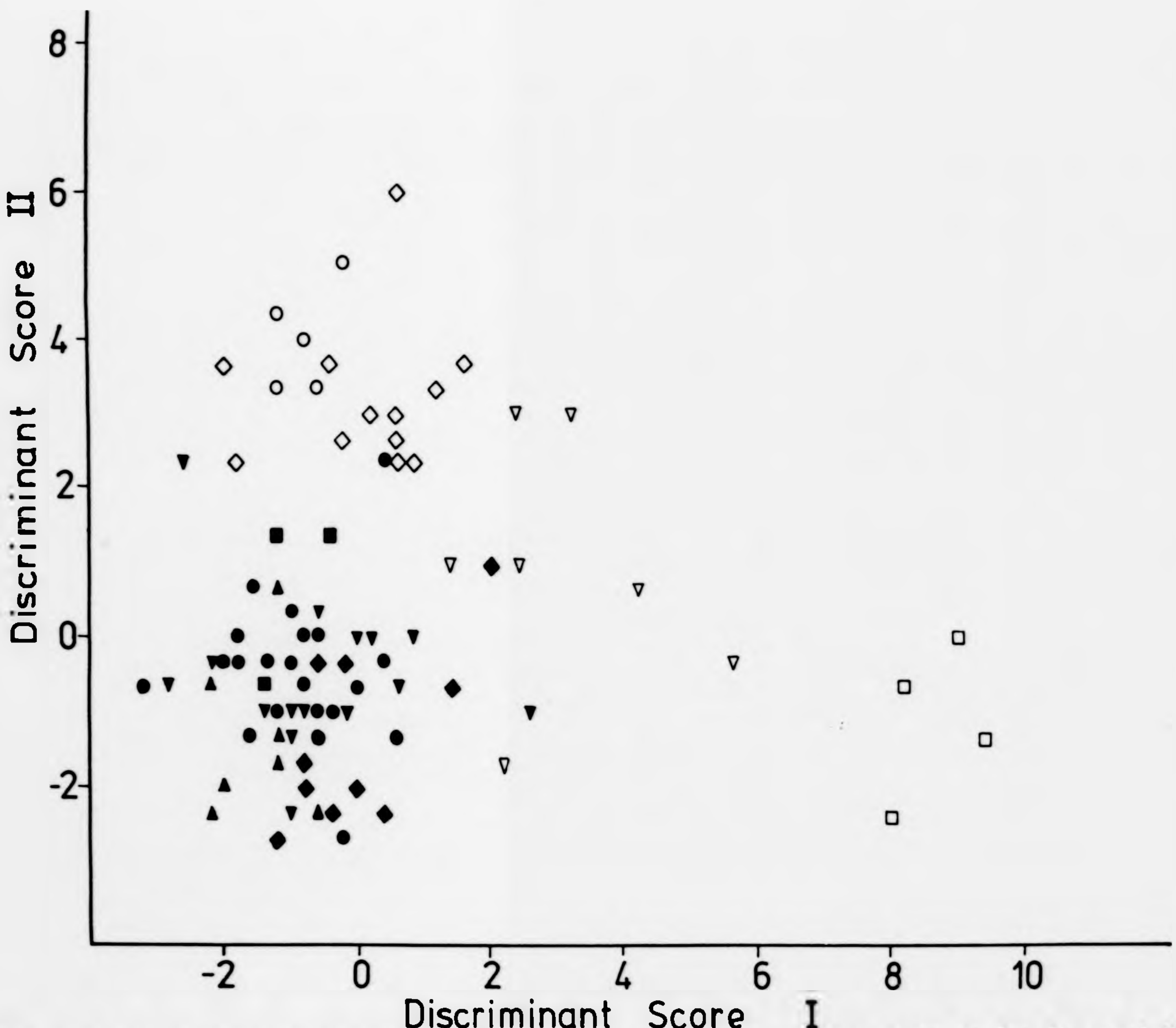


Figure 4.23: Plot of first two Discriminant Scores for all samples. (Key as for figure 4.2).

TABLE 4.21: STANDARDIZED DISCRIMINANT FUNCTION COEFFICIENTS FOR FIRST THREE FUNCTIONS, DISCRIMINATION BETWEEN FORMATIONS.

	All samples			Psammites/Semi-psammites			Semi-pelites		
	1	2	3	1	2	3	1	2	3
SiO_2	-1.57	4.12	1.71	1.23	3.08	-1.74	1.29	3.55	-0.71
TiO_2	-0.43	-0.58	-0.39	0.86	-0.26	0.83	-1.20	0.97	-0.23
Al_2O_3	-1.49	0.45	0.92	0.71	0.17	-2.40	2.02	0.85	-0.59
Fe_2O_3	-0.61	0.51	0.48	0.68	0.23	-0.66	1.57	0.06	-0.60
FeO	-0.72	0.85	0.27	0.40	0.25	-0.38	1.95	0.14	-0.34
MnO	0.13	1.33	3.21	0.40	0.27	-0.46	-0.36	1.10	-0.51
MgO	0.74	-0.34	-0.72	-0.28	-0.28	1.32	-0.15	-0.34	0.25
CaO	-0.29	-0.17	-1.48	0.06	0.35	0.28	0.42	-0.33	0.69
Na_2O	0.48	0.75	0.87	-0.09	0.58	-0.51	-0.73	0.59	-0.83
K_2O	-1.89	0.72	1.06	2.00	1.67	-0.29	-0.31	1.52	-1.42
P_2O_5	-0.37	0.31	-0.09	-0.42	-0.00	0.05	0.29	0.76	0.63
Rb	0.95	0.99	-1.10	-1.42	1.21	0.48	-4.52	-1.62	0.79
Sr	-2.29	-0.18	-0.02	1.29	-0.15	0.43	0.28	0.01	-0.83
Ba	-0.56	1.19	-0.06	0.17	-0.17	0.34	1.59	-0.83	-0.17
Ni	0.16	0.65	-0.18	-0.29	0.34	0.05	-0.34	1.35	1.53
Y	1.08	-0.18	0.47	-0.23	-0.66	0.30	0.57	-0.44	0.32
Cr	1.32	-0.51	0.38	-0.44	0.85	-1.36	-1.01	1.78	-1.31
Zr	-0.98	0.39	-0.38	-0.30	0.36	-0.41	-0.51	0.41	0.74
Nb	0.39	-0.15	-0.15	-0.05	-0.05	-0.07	0.21	0.02	0.11
Egnvl	21.21	4.34	3.05	4.87	2.56	0.91	15.32	5.85	2.28
Can.crl	0.98	0.90	0.87	0.91	0.85	0.68	0.97	0.93	0.83
% trace	67.8	13.9	9.8	49.5	26.1	9.2	58.2	22.2	8.7
λ	.0003	.0063	.0338	.0071	.0417	.1489	.0004	.0069	.0472
χ^2	342.8	212.6	142.2	445.0	285.7	171.4	256.4	164.2	100.7
Df.	152	126	102	152	126	102	114	90	68
Sign.	0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.005

TABLE 4.22: F MATRICES: FORMATIONS.

a/ All Samples.

Df.1 = 19. Df.2 = 78. Critical F ratio = 2.20 at 1% significance

	1	2	3	4	5	6	7	8
2	0.79							
3	0.49	2.17						
4	1.39	1.65	2.87					
5	10.42	15.35	16.09	12.27				
6	3.17	5.15	6.17	4.17	6.59			
7	1.98	4.16	4.27	4.97	11.98	3.85		
8	2.02	6.55	6.14	5.82	13.80	4.61	2.07	
9	1.02	1.73	0.98	2.30	13.71	5.71	4.21	5.69

b/ Psammites and Semi-psammites.

Df.1 = 19. Df.2 = 30. Critical F ratio = 2.70 at 1% significance.

	1	2	3	4	5	6	7	8
2	1.09							
3	0.51	2.07						
4	3.91	3.09	4.36					
5	17.62	10.36	28.76	12.75				
6	4.71	2.19	8.91	4.68	7.18			
7	3.02	3.05	4.98	3.85	14.93	4.63		
8	2.27	1.96	5.89	4.89	17.31	3.51	2.39	
9	0.39	0.87	0.59	2.46	10.42	2.93	1.52	1.21

c/ Semi-pelites.

Df.1 = 19. Df.2 = 22. Critical F ratio = 2.98 at 1% significance

	2	3	4	6	7	8
3	2.32					
4	4.56	1.76				
6	3.50	4.41	5.51			
7	4.84	4.49	5.23	4.38		
8	12.74	10.57	12.24	8.20	0.57	
9	2.12	0.81	2.68	4.12	4.65	10.95

1 = Carn Leac Semi-psammite
2 = Monadhliath Semi-pelite
3 = Knockchoilum Semi-psammite
4 = Coire nan Laogh Semi-pelite
9 = Tarff Gorge Semi-pelites
Corrieyairack Succession

5 = Gairbeinn Pebbly Semi-psammite
6 = Allt Luaidhe Semi-psammite
7 = Carn Dearg Psammite
8 = Creag Mhor Psammite

Glenshirra Succession

Discrimination between the formations is much less efficient and only some of the formations, particularly the Gairbeinn Pebbly Semi-psammite, can be distinguished from the others. There is however a clear distinction between formations from each of the two successions, and with more samples it may be possible to distinguish between all the formations.

e. Cluster Analysis.

Cluster analysis involves the classification of samples into more or less homogeneous groups, in such a manner as to reveal the relationships between the groups. It has been most commonly used in geology by palaeontologists for taxonomical classification purposes, but has also been applied to geochemical data, (Flood, Allen & Orme,1976, Merriam & Pena Daza,1976).

For the analysis, the variables are standardised in order that each element is weighted equally. (The mean value is subtracted from the variable and the result divided by the standard deviation giving a variable with a mean of zero and a standard deviation of one.) A measure of similarity is then computed between each pair of samples (n) resulting in an n x n matrix. The samples are then arranged into a hierachy so that the samples with the highest mutual similarity are placed together. The groups or clusters of samples are then associated with other clusters that they most closely resemble until all the samples have been placed into a complete classification scheme.

There are many different similarity measures and several clustering techniques; the program CLUSTAN 1B (Wishart, 1969) used here utilises several techniques of which Ward's Method (error sum of squares) clustering technique was selected. For a more complete discussion of cluster analysis see Anderberg (1973) or Davis (1973).

In contrast to discriminant function analysis, there are no tests of the statistical significance of the clusters formed; as with principal component analysis utility is judged by performance rather than by theoretical considerations.

The dendrograms produced by the CLUSTAN 1B program are shown in Figures 4.24 & 4.25. In each case SiO_2 was masked in the calculation of the similarity coefficients in an attempt to reduce the influence of rock type on clustering. (H_2O) was also masked as the values were calculated from LOI determinations and not considered to be relevant to the comparison of the original sediments.)

All rock types.

Rock type still has a marked influence on the clustering of the samples despite the masking of SiO_2 and the standardization of the data. This is a result of the constant sum nature of the data as SiO_2 rich rocks have lower concentrations of the other elements than SiO_2 poor rocks ie. the influence of rock type is due to the dominance of negative correlations in the correlation matrix.

Above a similarity coefficient of 6.00 there are 8 clusters: Cluster 1 is made up of samples from the Knockchoilum Semi-psammite with the semi-psammites from the Monadhliath Semi-pelite, the Coire nan Laogh Semi-pelite and two semi-psammites from the Glenshirra Succession. Cluster 2 is made up of samples from the Monadhliath Semi-pelite and together with Cluster 1 the concentrations of the elements deviate little from the overall mean values (low T in cluster diagonistics procedure RESULT). Cluster 8 contains the psammites from the Glenshirra Succession together with the quartzite sample (101A) from the base of the Monadhliath Semi-pelite. H_2O, FeO, Al_2O_3 TiO_2, MgO, Y and Cr concentrations differ substantially from the overall mean values and have low variability

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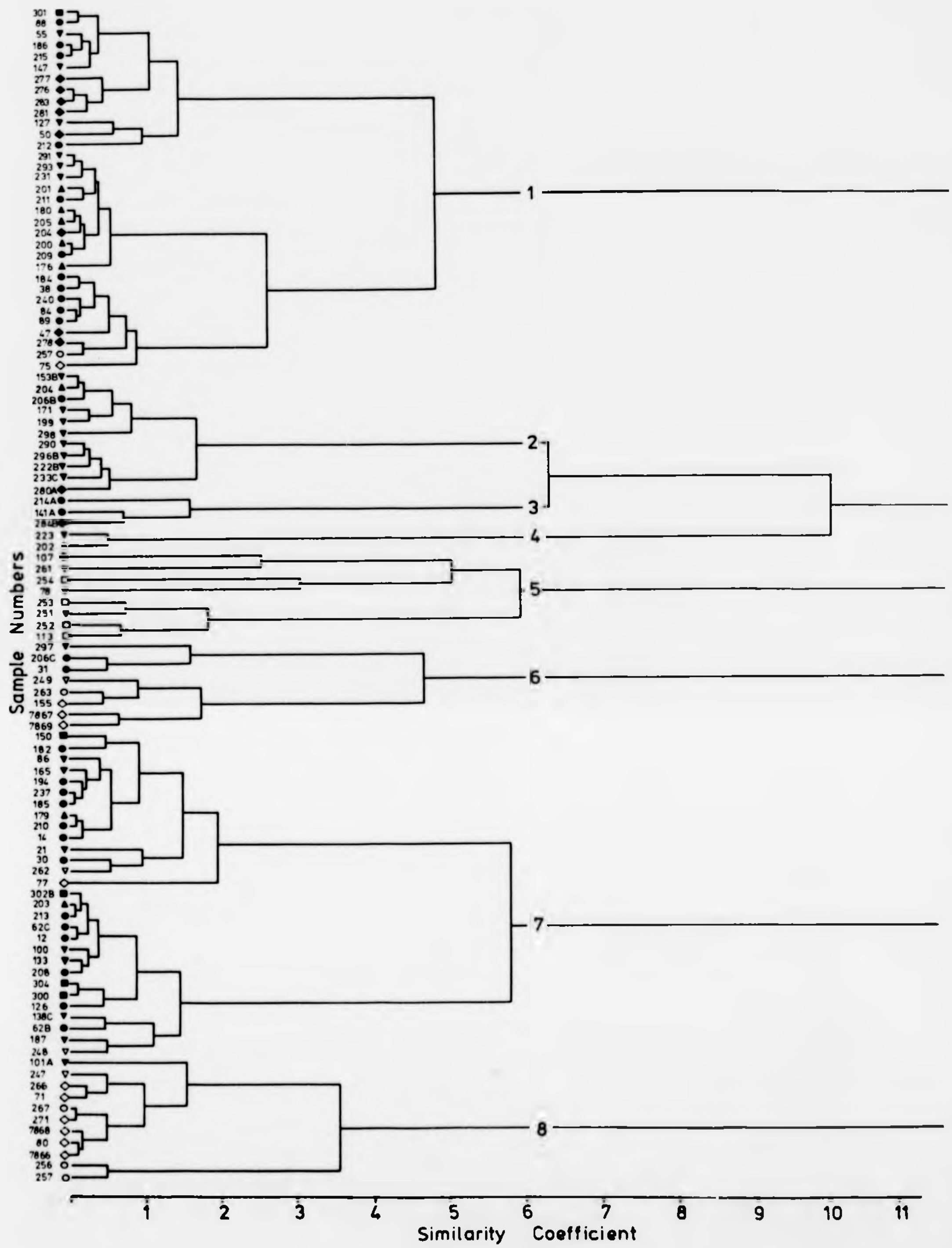


Figure 4.24: Dendrogram from cluster analysis of all samples.

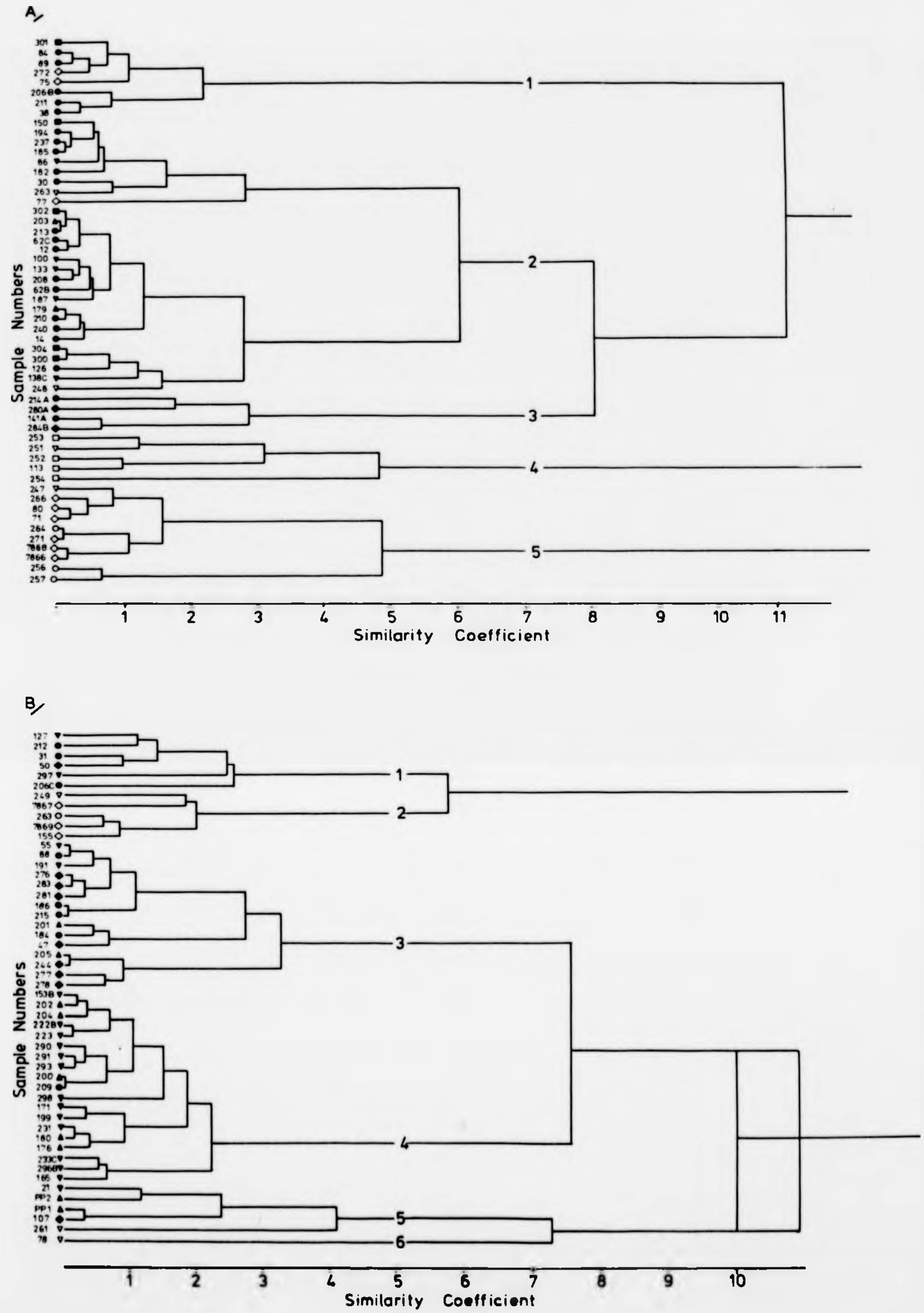


Figure 4.25: Dendrogram from cluster analysis of A) Semi-psammites and psammites, B) Semi-pelites.

compared with the overall variance (F-ratio) and are therefore diagonistic of the cluster (Wishart, 1969). The formations and successions are not well differentiated in the analysis and do not cluster together.

Psammites and semi-psammites.

Five clusters are present above a similarity coefficient of 6.082. Cluster 4 is made up of four samples from the Gairbeinn Pebbly Semi-psammite together with a single sample from the underlying Allt Luaidhe Semi-psammite. The cluster is characterised by Sr and Ba concentrations very different from the overall means, together with K_2O, Al_2O_3 and Y. CaO, MnO and Ni have low variances compared with the overall variance but have values very similar to the overall mean and so are not useful diagnostics of the cluster.

Cluster 5 is comprised of the psammites from the Glenshirra Succession and has significantly different values for Al_2O_3, Cr, MgO and FeO. From the other clusters FeO, Sr, MgO, P_2O_5, CaO, Ba and Cr also have low values of F-ratio and are therefore good diagnostics of the cluster.

Clusters 1, 2 and 3 are made up of the semi-psammites from the Corrieyairack Succession plus the semi-psammites from the Creag Mhor Psammite and Allt Luaidhe Semi-psammite. The different formations of the Corrieyairack Succession do not cluster together. The cluster analysis therefore distinguishes between the psammites of the Glenshirra Succession, and the Gairbeinn Pebbly Semi-psammites, but all the other samples cluster together.

Semi-pelites.

Above a similarity coefficient of 4.184 there are 6 clusters. Cluster 1 is made up of samples from the Corrieyairack Succession characterised by low variance and anomalous concentrations of K_2O and Y and low variance concentrations of Ni, FeO, Sr, Rb, Fe_2O_3 and TiO_2.

Cluster 2 is composed entirely of semi-pelites from the Glenshirra Succession characterised by values for K_2O, MnO, Sr, CaO and Na_2O very different from the overall mean.

Cluster 3 is composed of samples from the Knockchoilum and Coire nan Laogh Formations. The concentrations of each element varies little from the overall mean and therefore no elements are particularly diagnostic of the cluster.

Cluster 4 is made up of samples from the Monadhliath Semi-pelite with most of the samples from the Tarff Gorge, supporting the field interpretation which suggests that the two semi-pelites are equivalent. The element concentrations do not deviate significantly from the overall mean values.

Cluster 5 is made up of four samples with lower values for FeO than the overall mean possibly as there were more weathered than the others and PP1 and PP2 for which FeO was not determined. Sample PJH 78 forms Cluster 6, supporting the anomalous nature of its chemistry compared with the rest of the metasediments. It has concentrations of Sr, Cr, Zr, TiO_2, Fe_2O_3, CaO and Na_2O very different from the overall mean values, indicative of the presence of heavy minerals and possibly metasomatism.

Within the semi-pelites samples cluster analysis therefore reveals that the Glenshirra Succession can be distinguished from rocks of the Corrieyairack Succession and that the Monadhliath Semi-pelite can be distinguished from the Knockchoilum and Coire nan Laogh Formations.

f. Conclusions.

Multivariate statistical analysis of the geochemistry of the meta-sediments has revealed that there is a statistically significant difference between the two successions in the Corrieyairack Pass area, although only the Gairbeinn Pebbly Semi-psammite (formation) is distinctive on the formation level. The Monadhliath Semi-pelite is separated from the other formations of the Corrieyairack Succession in cluster analysis of the semi-pelites. It therefore appears that although differences between the formations from each succession can be recognised, the differences within the successions are not statistically significant. As the analysis of variance reveals that there are differences in the means for each element, the lack of adequate discrimination may be a result of insufficient data.

The statistical analyses support the conclusions of Section 2, that the variation in chemistry is controlled principally by variations in the proportions of feldspar and clay minerals, and also variations in the proportion of alkali feldspar to plagioclase. These variations are indicative of an arkosic immature nature of the Glenshirra Succession and relatively mature greywacke type of sediment in the Corrieyairack Succession.

CHAPTER 5 : SEDIMENTOLOGY

1. INTRODUCTION

2. SEDIMENTARY STRUCTURES
   a. Cross-lamination
   b. Graded Bedding
   c. Syndepositional Deformation Structures

3. PALAEOCURRENTS

4. ORIGIN OF CALCAREOUS PODS

5. LITHOLOGICAL VARIATION
   a. Corrieyairack Succession
   b. Glenshirra Succession

6. ENVIRONMENTAL INTERPRETATION

1. INTRODUCTION

As stated by Harris et al. (1978) "little sedimentological detail is available" for the Grampian Division "and any facies interpretations must remain at best highly speculative". The only detailed sedimentological interpretations that have been attempted in the Central Highlands, are those of; Hickman (1975), with reference to the Eilde Flags and the lower Dalradian of the Lismore to Glen Roy area, and Whittles (1981), with reference to the Grampian Division of the Loch Killin area. Hickman (1975) concluded that the Eilde Flags were deposited in a shallow shelf sea environment, recognising cross-bedding, small scale ripples, slump folds, graded bedding and heavy mineral layers, in a coarsening upwards sequence more than 1km thick. The Eilde Flags were described as poorly sorted arkosic sands, silts and muds, deposited from palaeocurrents of rapidly changing velocity. He suggested that the sediment maturity increases southwards, with the better sorted quartzites and schists of the Transition Group representing sedimentation further removed from the terrigeneous supply. In the Loch Killin area, Whittles (1981) also concluded that the dominantly psammitic, metasediments were deposited under shallow marine / sub-tidal conditions. He recognised features similar to those recorded by Hickman (1975) but also 'cut and fill' structures, and rhythmic graded bedding, resembling turbiditic deposits.

Thomas (1980) also recognised cross-bedding, small scale ripple laminations, current scours, and soft sediment deformation structures in the psammitic rocks of the Schiehallion area, and similarly suggested that these were indicative of a shallow water marine or deltaic environment, although he did not undertake any detailed sedimentological work.

2. SEDIMENTARY STRUCTURES

a. Cross-lamination.

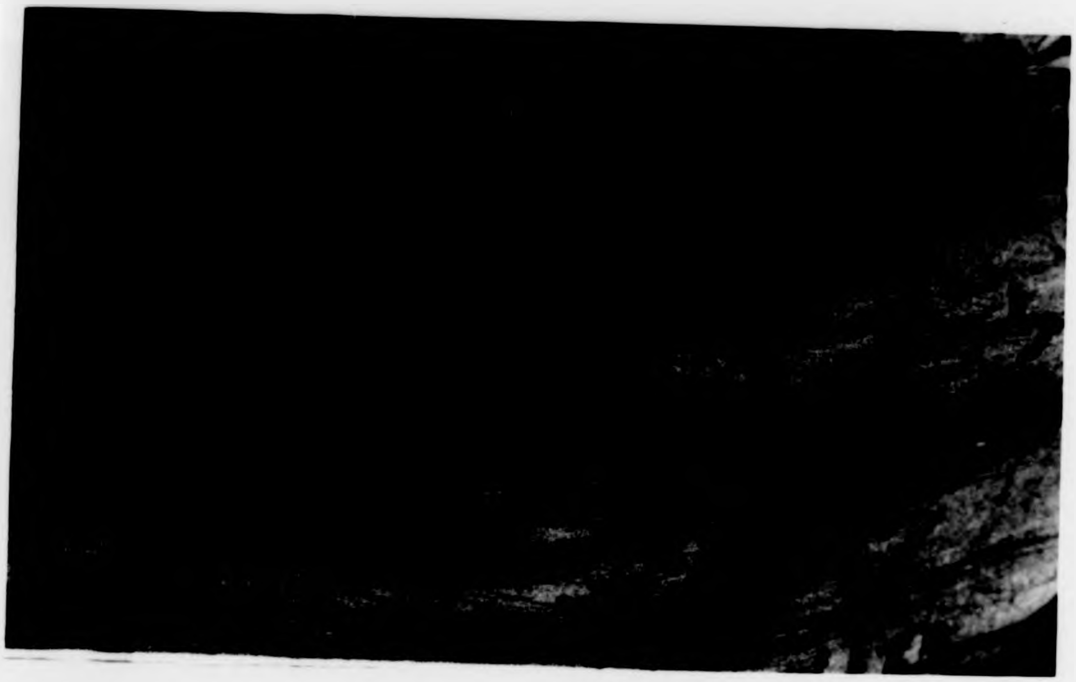
Cross-lamination is most commonly preserved within the lower portion of the Knockchoilum Semi-psammite, particularly in the River Tarff (NH 468032), in the Allt Yairack (NN 441981), and at NN 433971. It is also occasionally preserved within the Carn Leac Semi-psammite, the Allt Luaidhe Semi-psammite, and the Gairbeinn Pebbly Semi-psammite. Individual sets vary considerably in morphology (Plates 5.1 - 5.6) and size, with sets varying from 1cm to 4cm thick and cosets from 4cm to 25cm thick. At one locality (NH 450011), ripple marks are preserved on the bedding plane (Plate 5.2). These are straight crested, asymmetric ripples with a wave-length of 20cm and an amplitude of 0.5cm. Most of the ripples are considered to be current ripples with parallel foreset laminae varying from tabular to sigmoidal in shape and with planar or trough shaped bases. The variation in style indicates a variation from straight to sinusoidal crests attributed to variations in current strength (Reineck and Singh, 1973).

Variations in current strength are also indicated by the presence of muddy lenses within the ripple laminations, producing flaser structure or wavy bedding (Pettijohn,1975, Reineck and Singh,1973) (Plate 5.5). At one locality (NH 40200151), wave ripple laminations were recognised (Plate 5.6) in association with current ripple laminations.

Cross-lamination occurs in many different sedimentary environments but tends to be most abundant in shallow water sandy environments (Reineck and Singh, 1973).

Plate 5.1 : Cross-lamination in semi-psammite from the Knockchoilum Semi-psammite (NN 43659815)

Plate 5.2 : Ripple marks from Knockchoilum Semi-psammite (NH 45000110)



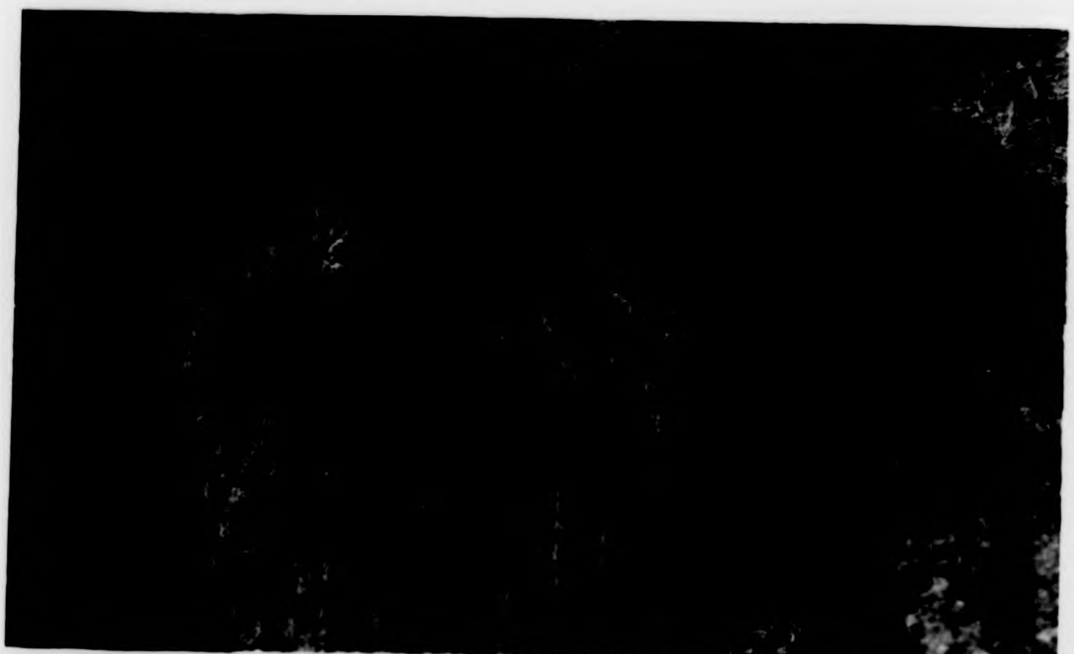


Plate 5.3 : Cross-lamination in semi-psammite from the Knockchoilum Semi-psammite (NN 43569964)

Plate 5.4 : Cross-lamination in semi-psammite from the Knockchoilum Semi-psammite (NN 43199782)

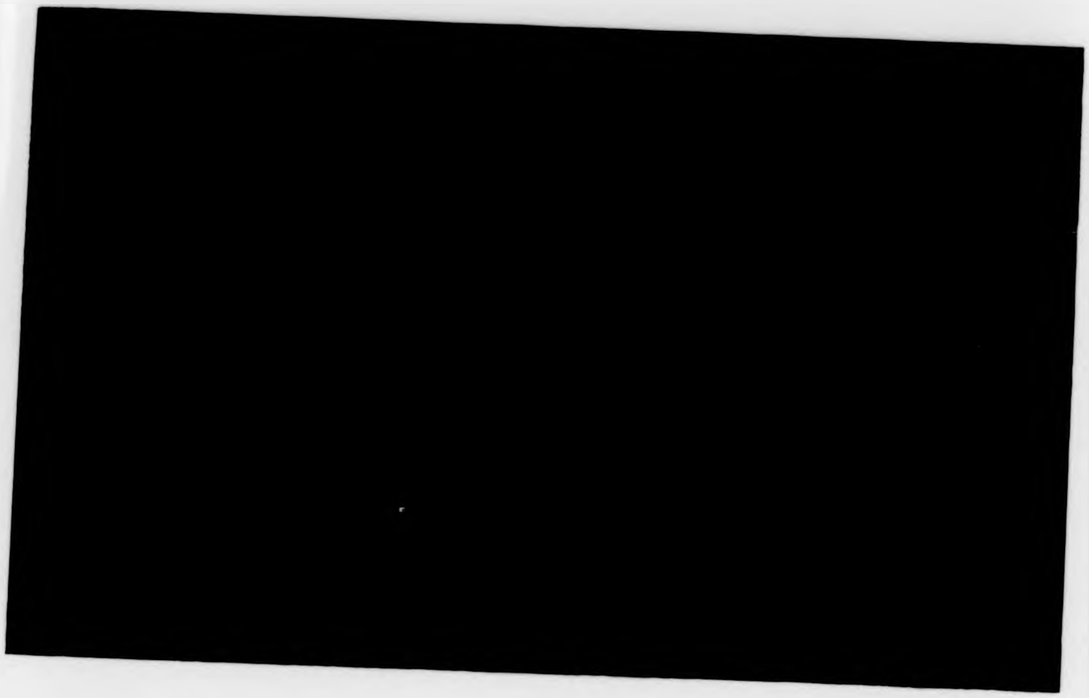
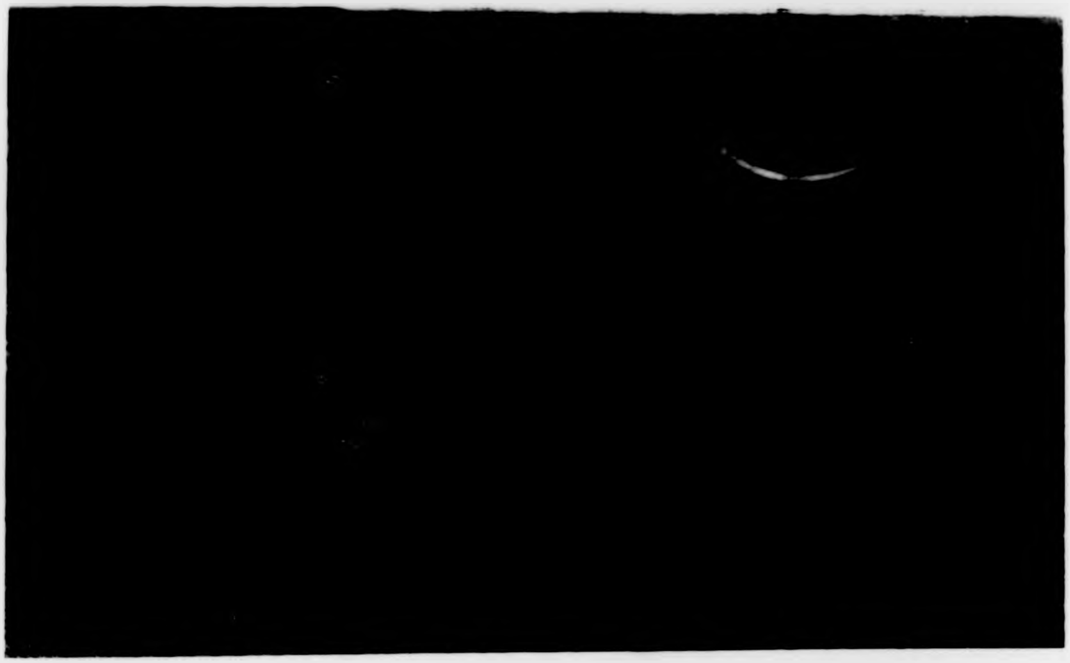
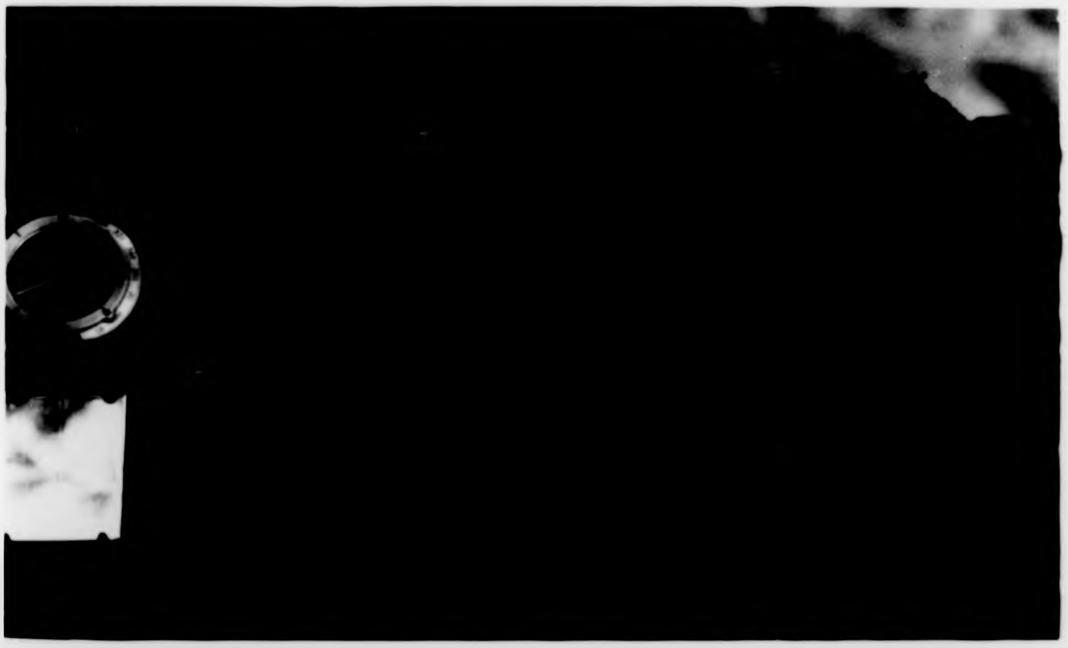


Plate 5.5 : Wavy bedding in the Knockchoilum Semi-psammite (NH 46800320)

Plate 5.6 : Wave ripple laminations in association with current ripple laminations in the Knockchoilum Semi-psammite (NH 40200151)





b. Graded Bedding.

Graded bedding is best preserved within the Gairbeinn Pebbly Semi-psammite, but was also recognised, locally, within the Knockchoilum Semi-psammite and the Carn Leac Semi-psammite. Within the latter two formations, the graded units are sporadically developed; singly or repeated only once or twice. These units vary from 2 to 15cm in thickness and generally involve a fining upwards from sand to silt or mud, with a sharp transition from mud to sand at the top of the unit. Coarser grade material was only rarely recognised; clasts never exceed 1 or 2mm in diameter (Plates 5.7 & 5.8). The thick rhythmic graded units recognised by Whittles (1981) in the Fechlin Psammite near Whitebridge were not recognised in the Corrieyairack area.

Reineck and Singh (1973 p.104) discuss the nature and origin of graded bedding from shallow water environments and state that they are generally and sporadically developed, as a result of sedimentation from suspension clouds in the last phases of a flood or from deposition during waning current activity.

In contrast, graded units are ubiquitous within the Gairbeinn Pebbly Semi-psammite and can be recognised even where the formation is highly deformed beneath the Gairbeinn Slide (Chapter 7).

The material in this formation is much coarsed than elsewhere with particles up to approximately 6cm in diameter. The graded units vary from 2 to 20cm in thickness, with a coarse grained gravelly base grading upwards into silts or muds with a sharp contact with the overlying gravel, (Plate 5.9). The silty portion of the unit is not always present, possibly due to penecontemporaneous erosion, and several metres of semi-psammite, semi-pelite or psammite occasionally intervene between successive

Plate 5.7 : Thin graded units, with scattered clastic fragments in the Knockchoilum Semi-psammite (NH 40180158)

Plate 5.8 : Repeated graded units, with local erosion surfaces in Knockchoilum Semi-psammite (NH 40180158)

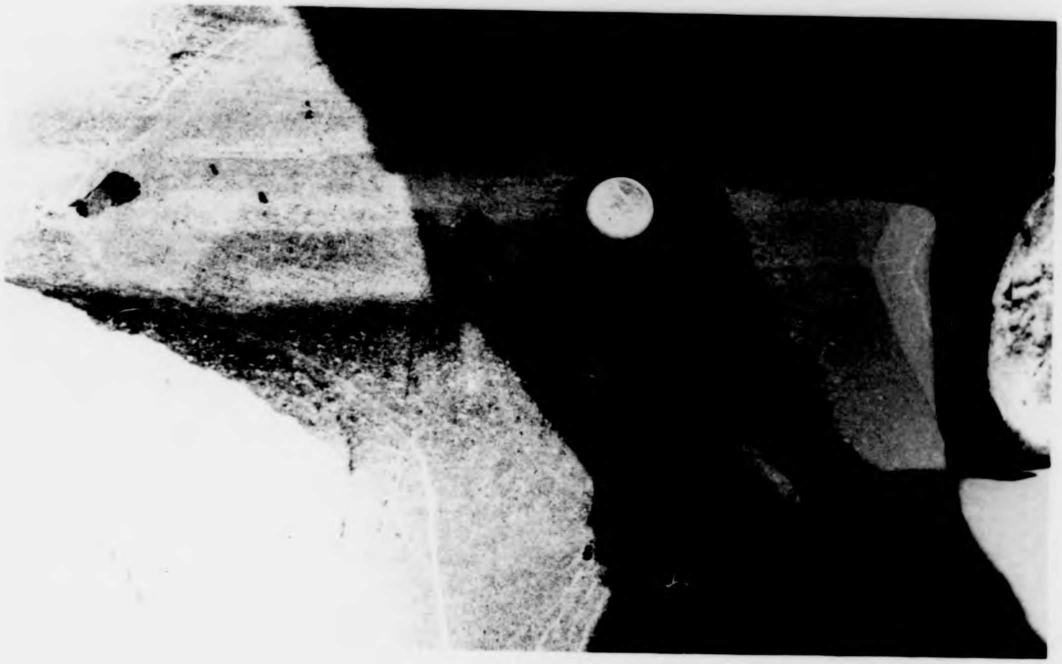


Plate 5.9 : Graded units with abundant clastic fragments and local erosion surfaces, Gairbeinn Pebbly Semi-psammite (NH 47159923)

Plate 5.10 : Convolute lamination within the Fechlin Psammite (NH 4680275)

pebble bands. However, these units also show grading on a scale of 2-4cm and have irregularly distributed clastic fragments (Chapter 2). Their form suggests a highly variable discharge of material from variable currents, combined with rapid deposition.

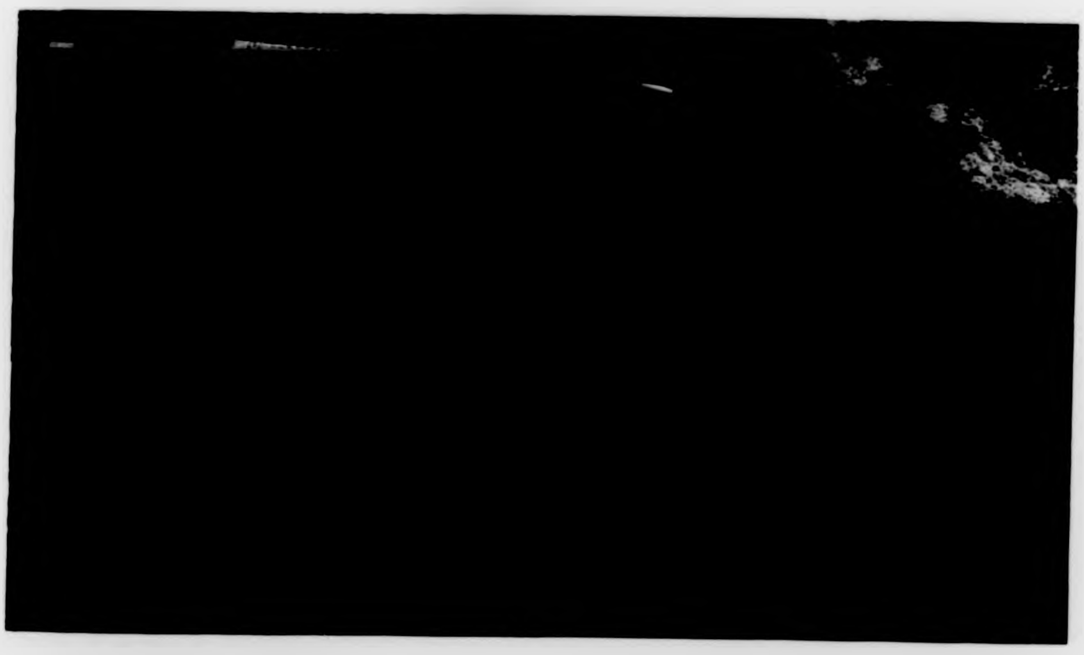
c. Syndepositional Deformation Structures.

Convolute bedding occurs principally within the Fechlin Psammite (NH 468027), but is also locally developed within the Knockchoilum Semi-psammite. The structures are characterised by fine laminations, folded into broad synclines and sharp anticlines, with local overturning (Plates 5.10 & 5.11). The folds are orientated normal to the palaeocurrent, with the overturning predominantly in the downcurrent direction (Blatt, Middleton and Murray, 1980), indicating deposition from northerly flowing currents (Section 3).

Many theories have been advanced to explain these structures involving different mechanisms to explain the liquefaction of the sediment so that it deforms or flows under very small shear stresses (Blatt, Middleton and Murray, 1980 p.189). The structures appear to be restricted to coarse silt or fine sand grade material, which has been rapidly deposited from suspension, resulting in unstable packing and low cohesion but with a low permeability preventing the rapid loss of pore fluids. A sudden change in the packing as a result of an earthquake or other disturbance, generates high excess pore-pressures and produces liquefaction of the sediment (Blatt et al.op.cit.). Liquefaction may also be a result of overloading, for example, due to deposition of sand on top of the bed (McKee and Goldberg, 1969) or due to current activity producing vortices (Kuenen, 1953) or as a result of subaerial exposure, with compaction of the sediment resulting from the expulsion of water.

Plate 5.11 : Convolute laminations within Knockchoilum Semi-psammite in part of rhythmic bedding (Fig 2.3) also showing local erosion surface. (NH 40180158)

Plate 5.12 : Overturned cross-lamination in Knockchoilum Semi-psammite. (NH 42230490)



Convolute bedding was regarded as typical of turbidite sequences but it is also locally abundant in inter-tidal flats and fluvial flood plain or point bar deposits (Reineck and Singh, 1973).

Overturned cross-laminations (Plate 5.12) were observed within the Knockchoilum Semi-psammite and are also considered to be a result of partial sediment liquefaction, possibly as a result of earthquake shock, with the overturning related to shear stress exerted by current drag (Allen and Banks, 1972). Anderton (1976) states that these syndeposit-ional structures are uncommon in shallow marine sediments and that their presence in these environments is evidence for earthquake activity.

3. PALAEOCURRENT ANALYSIS

As sedimentary structures suitable for accurate measurement of palaeocurrents are only sporadically developed within the Corrieyairack Pass area, no systematic analysis of the palaeocurrents has been undertaken. However, the direction of overturning of the convolute bedding and cross-lamination and the attitude of most of the cross sets, indicate a general northeasterly palaeocurrent direction. Rotation of the beds about the main D2 phase of deformation is usually parallel to the observed current direction and so does not affect the estimated direction. The effects or D1 and D3 are more difficult to estimate, particularly as the Corrieyairack Succession must be considered to be allochthonous, and both episodes may have resulted in considerable rotation.

If the model of D1 recumbent folds proposed for the Tarff section and therefore the whole area (Chapter 7) is correct, then D1 and D2 events were probably co-axial, and any rotation of the current directions is limited to D3 events.

4. ORIGIN OF CALCAREOUS PODS

As outlined in Chapter 6 the calcareous pods, the white calc-silicates, calcite bearing pods and green calc-silicates are considered to be carbonate concretions of diagenetic origin. Unfortunately there appears to be no particular environmental significance attached to the occurrence of carbonate concretions, as they can be found in a wide range of sedimentary environments including fluvial, deltaic, shallow marine or deep sea.

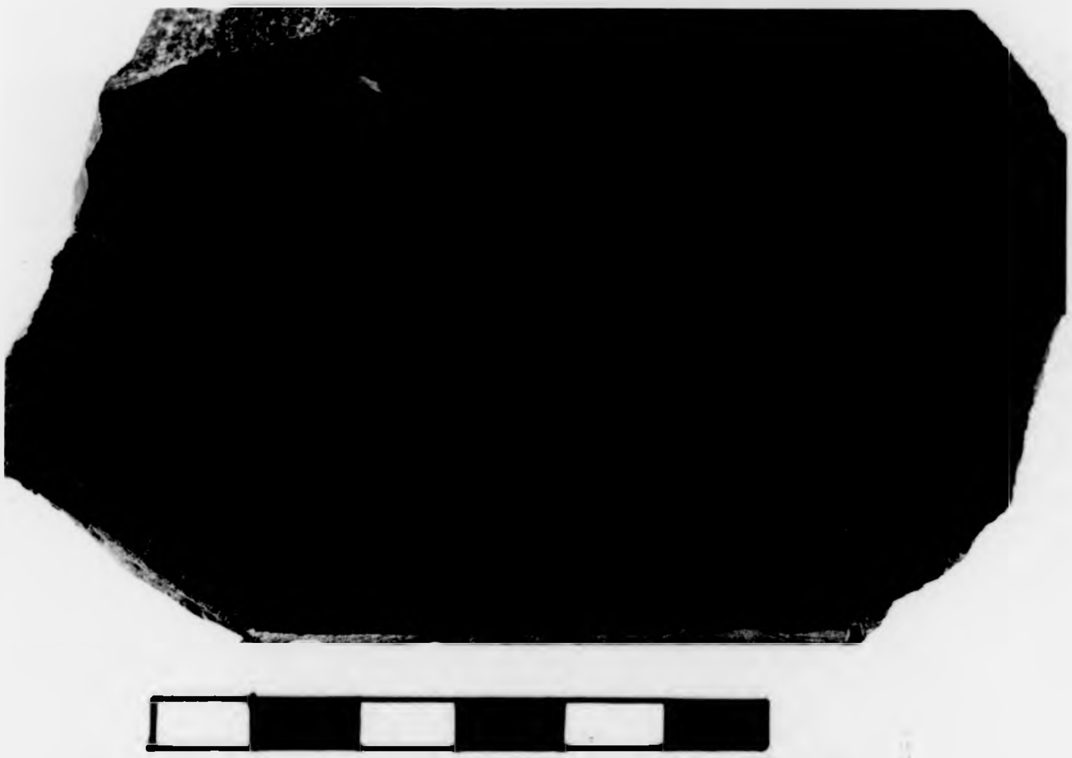
Carbonate does not normally precipitate in water below a pH of 7.8, and above a pH of 8.3 becomes insoluble, thus preventing the movement of carbonate in pore fluids necessary for the concretions to develop. However, these conditions are fulfilled in most marine and fluvial systems (pH 7.5 to 8.5) (Weeks,1957, Allegre and Michard,1973).

A post-depositional, pre-compaction or diagenetic rather than epigenetic origin for the concretions is proposed, as the pods are often seen to overgrow sedimentary structures such as cross-laminations (Plate 5.13), without disturbance of the stratification.

The mechanism of formation proposed by Raiswell (1971) involves the upward migration of pore water, rich in dissolved CO_2, through the uncompacted sediment, as a result of capillary action. As the pore water rises, CO_2 is released due to equilibration with decreasing pore pressures at decreasing depth. As the migration of the pore water continues, it becomes supersaturated in carbonates and precipitation occurs. Supersaturated zones are often established at bedding planes, as a result of changing permeability, of for example, sandstones and siltstones. Once a concretion nucleates, a chemical potential is developed and carbonate ions migrate by diffusion through the pore water to the point of nucleation.

Plate 5.13 : Cross-lamination preserved in calcite bearing pod from Knockchoilum Semi-psammite.
(NH 39500215)

Plate 5.14 : Calcite bearing pod in Knockchoilum Semi-psammite, showing characteristic pitted appearance as a result of preferential erosion of calcite.
(NH 40200155)



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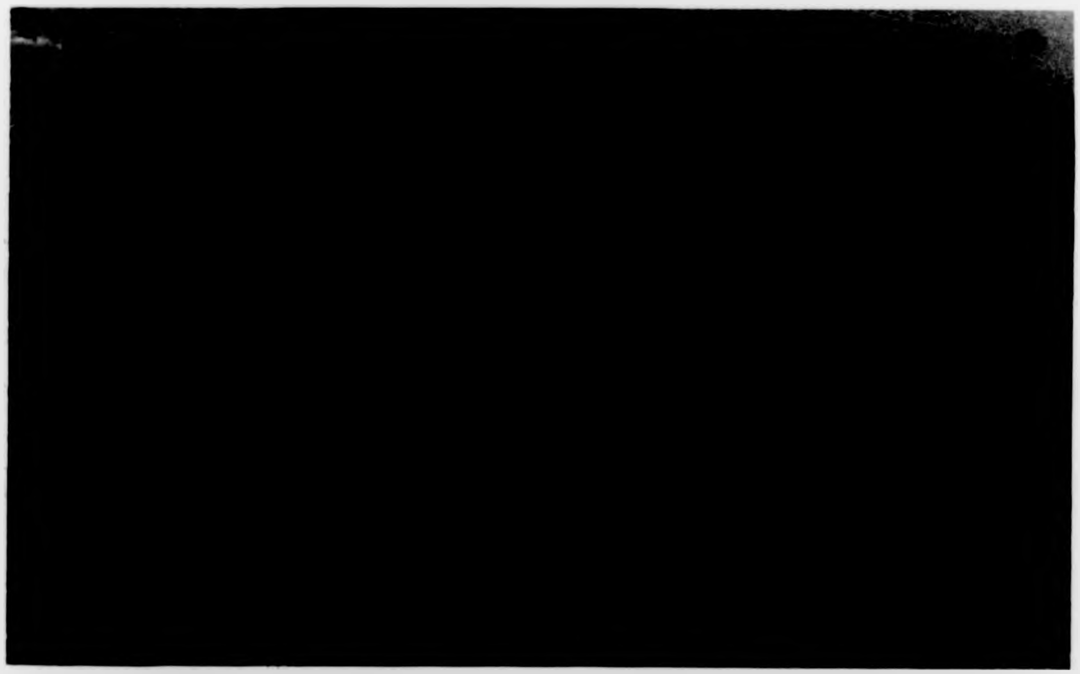

Deegan (1971) suggested that secondary silica cement was actually replaced by carbonate nucleating along the boundaries between detrital grains and eventually replacing the detrital grains themselves. This process would involve the solution of silica by slightly acidic CO_2 rich pore water:

$$\underset{}{SiO_2} + \underset{\text{carbonic acid}}{2H_2CO_3} = \underset{\text{silicic acid}}{H_4SiO_4} + 2CO_2$$

The release of CO_2 results in an increase in the alkalinity of the pore water, allowing precipition of carbonate. If quartz or the secondary silica cement was the only material to be replaced, there would be a decrease in the SiO_2/Al_2O_3 ratio compared to the host rock as recorded by Tanner (1976), but this was not observed in the Corrieyairack area (Chapter 6). It is thought, therefore, that feldspar is also replaced during the formation of the concretion.

The shape of the concretions varies from the ellipsoidal pods of the Knockchoilum Semi-psammite (Plate 5.14) and the Creag Mhór Psammite, to the thin, laterally extensive bands of the Monadhliath Semi-pelite and Coire nan Laogh Semi-pelite, and is inferred to be a result of differences in the nature of the permeability anisotropies in the different lithologies. The calc-silicate bands of the semi-pelitic formations are restricted to thin psammitic ribs which, presumably due to the lack of clay minerals, have an increased permeability compared with the relatively impermeable semi-pelites. Permeability anisotropies are therefore planar producing planar concretions. In contrast, the semi-psammites are relatively isotropic and concretions nucleate at a series of points rather than along a particular surface, probably producing more or less spherical concretions which have been subsequently flattened by compaction and tectonism.

The zoning in the calc-silicates is a result of slow diffusion rates and is particularly diagonostic of concretions formed later in the diagenetic history of the sediment (Raiswell, 1971).

Plate 5.15 : White calc-silicate band in semi-pelite, from Monadhliath Semi-pelite (NH 41080054)

5. LITHOLOGICAL VARIATION

a. Corrieyairack Succession.

The metasediments of the Corrieyairack Succession can be divided into three lithofacies, making up the five formations of the Succession (Chapter 2). These are:

i. Semi-pelites, representing mud and silt deposits with thin ribs of sand, concretions and thicker lenses of clean washed sands, represented by the quartzites. Heavy mineral bands occur within the quartzites but no sedimentary structures were observed. This facies makes up the Coire nan Laogh and Monadhliath Semi-pelites. (More detailed descriptions of the formations and therefore the facies can be found in Chapter 2.)

ii. Semi-psammites and Psammites, representing poorly sorted sands with occasional silt lenses. Ripple marks, wave and current ripple laminations, convolute bedding, overturned cross-lamination and a few, thin bands of coarser sand, in sporadic graded beds are found, within planar or tabular beds, ranging from 0.04 to 1m thick. Concretions are found throughout. Locally, massive semi-psammites, graded beds and convolute beds are repeated in cycles (Fig 2.3). This facies makes up the Carn Leac Semi-psammite, the Knockchoilum Semi-psammite and the Fechlin Psammite.

iii. Striped Psammite/Semi-pelite. This facies is much more locally developed and is transitional between facies i. and ii. at the top of the Knockchoilum Semi-psammite. It consists of rapidly alternating but laterally extensive, alternations of sands and silts, in planar beds, varing from 4 to 30cm thick. No sedimentary structures or concretions were recognised.

b. <u>Glenshirra Succession.</u>

The Glenshirra Succession can be divided into four lithofacies corresponding to each of the formations:

i. Mixed Facies of the Creag Mhor Psammite, represented by alternations of sands, muds and silts, occasionally in cyclic repetition (Fig 2.2). Concretions occur within the sandstone units but no other sedimentary structures were recognised.

ii. Psammite of the Carn Dearg Formation, consisting of massive feldspathic sands with occasional thick lenses of silts or muds. No sedimentary structures were observed.

iii. Semi-psammite of the Allt Luaidhe Formation, representing a transitional facies between the sands of facies ii. and the pebbly sands of the Gairbeinn Semi-psammite. The sands are interbedded with silt and mud locally in planar beds 5 to 10cm thick and elsewhere as more extensive lenses. Concretions are sporadically developed and cross-laminations were also observed.

iv. Pebbly Semi-psammite, consisting of coarse grained gravels and sands with subsiduary silt or mud and fine grained sands. The facies contains abundant graded beds, some cross-lamination and a few concretions. The individual gravel units are lenticular in shape and locally separated by extensive thicknesses of interbedded sands and silts.

6. ENVIRONMENTAL INTERPRETATION

Any palaeogeographical or environmental interpretation of the sequence of metasediments in the Corrieyairack area, is necessarily extremely tentative, as a result of the lack of exposure preventing detailed study of the sedimentology. The complex metamorphic and structural histories also tend to obliterate or confuse the diagnostic features.

Major thicknesses of sands, such as those of the Fechlin Psammite, Knockchoilum Semi-psammite, Carn Leac Semi-psammite, and Carn Dearg Psammite are likely to be formed only in three main sedimentary environments : fluvial, deltaic or shallow marine. Within the Knockchoilum Semi-psammite, particularly where sedimentary structures are more commonly preserved, the following features support a shallow marine origin for the sediments:

i. The dominance of planar or tabular beds, with individual units traceable over tens of metres, and a complete lack of lenticular beds with major erosion surfaces indicative of channelling.

ii. The lack of any preserved clastic fragments.

iii. The lack of large scale cross-bedding.

iv. The fairly random vertical sequences (Anderton, 1976) with little indication of cyclic repetition.

v. The presence of small scale wave and current ripple laminations, and the wide variation in style of these structures (Reineck and Singh, 1973, Walker,1979).

vi. The sporadic and solitary nature of any graded bedding.

vii. A geochemistry characteristic of marine sequences (Chapter 4).

Johnson (1978) recognised three main lithofacies in shallow marine siliclastic seas:

A. Sandstone facies: comprising 90-100% sandstone, with parallel lamination reflecting an upper flow regime, combined with deposition from suspension, caused by either current or wave action. Cross-lamination reflects a lower regime with the migration of small scale wave or current ripples.

B. Heterolithic facies: comprising thinner bedded deposits with a variable sand content. This facies is divided into three subfacies: sand dominant (75-90% sand), mixed (50-75% sand), and mud dominant (10-50% sand). The sands occur as parallel sided, laterally persistant sheets, 5-20cm thick in the said dominant facies but only 3-10cm in the other subfacies. The variability of sand content reflects fluctuations in the hydrodynamic conditions and sediment supply.

C. Mud facies: consisting of muds or silts, with thinly graded beds resulting from deposition from suspension.

It is proposed that these three lithofacies broadly correspond to the lithofacies described fron the Corrieyairack Succession, and that they co-existed laterally within a shallow-marine environment. The Coire nan Laogh Semi-pelite was possibly deposited in the deeper distal part of the shallow shelf sea, as muds and silts corresponding to facies C. of Johnson (1978). A period of regression, due to a drop in the relative sea level or possibly sediment supply exceeding the rate of subsidence, resulted in the rapid progradation of facies A. and deposition of the Fechlin Psammite and Knockchoilum Semi-Psammite. A regime of gradual subsidence relative to sea-level together with a plentiful supply of terrigeneous material, must be invoked to account for the large thickness of these two formations. However, at some stage, with a rise in the relative sea level, or a period in which subsidence exceeded sediment supply, a slow period of transgression ensued, producing the local development of the transitional heterolithic facies B. followed by the Monadhliath Semi-pelite facies C. Progradation of the sandstone facies is repeated with the deposition of the sands of the Carn Leac Semi-psammite.

Quartzite bands within the Coire nan Laogh and Monadhliath Semi-pelites may represent the effects of short periods of progradation of the sandstone facies. The thinner quartzites are possibly due to storm activity (Anderton, 1976).

The Glenshirra Succession, due to the lack of sedimentary structures in the lower part of the Succession and the contrasting facies of the Gairbeinn Pebbly Semi-psammite, is a little more problematical.

Any interpretation of the Gairbeinn Pebbly Semi-psammite must explain the following features:

i. The texturally, mineralogically, and geochemically immature nature of the sediment.

ii. Extensive lenticular gravel deposits within thin graded units.

iii. Sandstone and siltstone deposits between successive gravel deposits, occasionally showing cross-stratification.

iv. The overall coarsening-up sequence of the formation.

v. The contrast with the underlying sediments.

Although gravel deposits are found within shallow marine environments, these deposits are generally of small volume and occur as narrow linear belts parallel to the shore line (Pettijohn, 1975).

The thickness of gravel deposits, formed by fluvial processes in alluvial fans or braided streams, is many times greater than those of strandline deposits. Present day alluvial fans are of vast extent and characterise regions of high topographic relief (Rust, 1979), implying tectonic activity during or immediately prior to deposition (Collinson, 1978).

It would seem therefore, due to the large thickness and extensive nature of the gravel deposits of the Gairbeinn Pebbly Semi-psammite that the deposit is unlikely to have originated in a shallow marine environment but is of fluvial origin.

A continental origin for the sediment is supported by its geochemistry (Chapter 4). It is extremely immature chemically, suggesting that it is a proximal deposit and has high Sr values, high Sr/Ca and K/Rb ratios, indicative of continental deposits (Wedepohl,1969, Campbell and Lerbekmo,1963).

Alluvial gravels occur in two principal environments; alluvial fans and braided streams on alluvial plains (Rust, 1976). However, the distinctions between these two environments are rarely apparent in ancient sediments. Braided streams differ from alluvial fans principally in the lack of debris flows, recognised as extensive units of massive, poorly sorted, muddy, matrix supported gravels. They also show more gradual facies changes downstream.

The gravels and sands of both environments are characteristically immature, frequently arkosic and typically red, as a result of deposition in an oxidising environment (Blatt, Middleton and Murray, 1980). Highly variable discharge is also typical, and the transient nature of deposition is manifest by thin sedimentary units, showing both lateral and vertical variations in grain size and the nature of internal stratification. This reflects changes in current velocity and depth over short periods of time and space (Smith N.D., 1970). Individual units show fining upward grading, near horizontal bedding or cross-laminations (Collinson, 1978).

Proximal fan deposits are dominated by crudely horizontally bedded gravels (Collinson, 1978), with an increase distally in cross-stratified sets and minor deposits of horizontally laminated sands and muds (Rust, 1976). The deposits of braided streams are chiefly composed of sand and gravels in lens shaped channel fills (Allen J.R., 1970).

The contrast of the Gairbeinn Pebbly Semi-psammite with the underlying formations may be explained by postulating a rapid uplift of the source area during deposition of the transitional Allt Luaidhe Semi-psammite. This produced the high topographic relief characteristic of braided stream or alluvial fan environments. Continuing uplift during deposition of the Pebbly Semi-psammite also explains the large thickness and extensive nature of the formation, particularly if it is continuous with the 3km thickness of conglomerate recorded at Fort Augustus (Parson, 1979) (Chapter 7), and also the overall increase in grain size up through the formation.

The remainder of the Glenshirra Succession consists of large thicknesses of parallel bedded sandstones. This is also thought to be of shallow marine origin due to the lack of evidence to the contrary. The Carn Dearg Psammite is possibly equivalent to facies A of Reading (1979) and the Creag Mhor Psammite to the sand dominant facies B.

The differences between the two successions may be the result of different source areas, the arkosic nature of the Glenshirra Succession suggesting a granitic source area (Chapter 4). Alternatively, they may be a result of the differing effects of currents within the shallow marine environment, or possibly, a result of variations in topographic relief of the source area. The Glenshirra Succession may represent the more proximal deposits, of a land mass of high relief, with deposition in a high energy, oxidising environment (Chapter 4) combined with rapid deposition and possible subaerial exposure in both the lower part of the succession and in the Gairbeinn Pebbly Semi-psammite.

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